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Arthur D. Little, Inc, Cambridge, Mass.

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THE IMPACT OF PRODUCING LOW-SULFUR, UNLEADED MOTOR GASOLINE ON THE PETROLEUM REFINING INDUSTRY: VOLUME I - PROJECT SUMMARY

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Air and Waste Management
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I. EXECUTIVE SUMMARY

A. INTRODUCTION

This report summarizes a study performed for the Environmental Protection Agency, which was part of a three-phase program undertaken in parallel using a similar conceptual approach and data base. The other two studies are entitled, "The Impact of Lead Additive Regulations on the Petroleum Refining Industry" and "The Impact of SO_x Emission Controls on the Petroleum Refining Industry", published as EPA report numbers EPA-450/3-76-016a,b and EPA-600/2-76-161a,b, respectively. Significant synergy of data gathering, scenario development, computer simulation time and subsequent analysis was achieved by performing the three separate studies as part of an integrated work program. However, the combined cost of implementing all three regulations cannot be obtained by direct summation of the results of the three individual reports.

Initial work on this program began in late 1973. An interim Phase I report was published in May, 1974, entitled "Impact of Motor Gasoline Lead Additive Regulations on Petroleum Refineries and Energy Resources - 1974-1980, Phase I", EPA report number 450/3-74-032a. In this Phase I study, the U.S. refining industry was simulated as a single composite model which allowed a rapid overview analysis, but lacked in the desired level of precision.

Accordingly, a more detailed simulation of the U.S. refining industry was developed via a "cluster" model approach which was used in this three-phase effort. This project included collection and collation of an extensive base of refinery data supplied by the Bureau of Mines and individual oil companies which was used to achieve satisfactory calibration of the cluster models. It is felt that the development and calibration of the cluster models represent a significant achievement in the area of refinery simulation.

In the present report, several scenarios are developed to describe how the petroleum refining industry will likely operate for the next decade, with and without possible regulations controlling the sulfur level of unleaded gasoline to either 100 ppm or 50 ppm, thereby reducing sulfate emissions from automobiles employing catalytic converters. The report then summarizes the detailed planning assumptions required to execute the task, along with the methodology used to develop these assumptions. The primary study results are then presented herein, defining the impact of control of sulfur in unleaded gasoline in terms of capital investment requirements, increased refining costs per gallon of unleaded gasoline, and energy penalties. A complete presentation of planning assumptions, calculational methods, and study results is contained in the appendices of Volume II of this report.

B. SCOPE AND APPROACH

The objective of this study is to determine the impact on the petroleum refining industry of a limitation on the sulfur content of unleaded gasoline (a) to an average level of 100 ppm and (b) to an average level of 50 ppm.

The specific goals of the study are to determine for the period through 1985 the impact of the control of sulfur content of unleaded gasoline in terms of (a) capital investment requirements; (b) composite increase in refining costs per gallon of low sulfur unleaded gasoline, including return on capital, manufacturing cost, and yield losses; (c) increased crude oil requirements; and (d) net energy penalties, reflecting increased crude oil requirements less the heating value of increased refinery byproducts such as liquefied petroleum gases (LPG).

In the study, limitations of present and future refinery configurations are taken into consideration. However, considerations outside the scope of the study include availability of capital requirements, impact upon the competitive structure of the industry, ability of the construction industry to meet the associated refinery construction needs, and costs of distribution and marketing of low sulfur unleaded gasoline. The study focused upon the large, complex refineries processing about three-fourths of the crude oil refined in the United States. The impact upon the small refineries comprising over half of the number of U.S. refineries has not been fully assessed. On a relative basis, the penalties to the small refiner probably exceed those reported herein.

In approaching this problem, it was recognized that there are many complex interactions in the petroleum refining industry. Also, there is a necessity for compromises between various process routes for making low sulfur unleaded gasoline, including consideration of their capital investments and manufacturing costs. Therefore, a standard analytical tool of the petroleum industry was applied to this problem, computer refinery model simulation with an associated linear programming (L.P.) optimization algorithm. This provided an assessment of the impact of the control of unleaded gasoline sulfur content with an optimal, minimum cost selection of processing and blending schemes to achieve this end.

Although this analytical method has been used by the petroleum industry for more than a decade for studies of individual refineries, its use in simulation of the entire U.S. refining industry has been limited. Therefore, one of the requirements of this program was the development of a methodology for industry-wide simulation, collection and utilization of a data base to confirm the utility of this methodology, and definition of a means to utilize model results to determine national implications of a proposed policy. Equally important was the careful assessment of the planning assumptions regarding the constraints which may be imposed on the petroleum refining industry over the next decade. In all of these activities, Arthur D. Little, Inc., cooperated extensively with representatives of the Environmental Protection Agency and with members of a task force comprised of representatives of the American Petroleum Institute (API) and the National Petroleum Refiners Association (NPRA). As a result of these efforts, the utility of the model in faithfully representing the likely behavior of the petroleum refining industry over the next decade was greatly enhanced.

The modeling approach developed in this study provided for a specific simulation of the existing U.S. refining industry, processing domestic crude oils, including Alaskan North Slope crude oil, to the extent available. Any additional crude oil required to meet petroleum product demand was assumed to be imported. Two simulation models, called "grassroots models", were developed to provide for any new refining capacity which would be required to meet product demands in 1980/1985. The grassroots model for the western U.S. used North Slope crude oil, whereas a separate grassroots model for the eastern U.S. used imported oil.

The existing U.S. refining industry was simulated by six individual computer models, constructed to represent clusters of three refineries each in six geographical areas of the United States. These cluster models, therefore, represented refineries typical of the refining industry in terms of crude oil type, processing configuration, and product slate. They ranged in crude oil capacity from 48,000 to 350,000 bbls/day. To ensure that the cluster models adequately represented the industry, an extensive data base on these 18 refineries was collected and analyzed. Processing yield and property data was assimilated to ensure adequate representation of the refinery processes and blending operations. Finally, each cluster model was calibrated by comparison to the extensive data base.

In addition, a methodology for scaling up the results of the cluster models to the entire United States was developed, including these 18 cluster model refineries as well as atypical refineries. In a comparison with 1973 Bureau of Mines data, the most recent year for which complete information was available, the total petroleum products output and crude oil consumption predicted by the model agreed with Bureau of Mines data within 2%. This scale up technique allows assessment of the national impact for the four specific goals of the present program, including an estimate of the impact on small refiners.

Several planning assumptions were required; each of these required auxiliary studies of considerable detail, because of the importance of these planning assumptions to the study results.

Since the difficulty of controlling the sulfur content of unleaded gasoline is dependent on the nature of the crude oil being refined, a separate study was made to determine the types of crude oil to be processed by the U.S. refining industry over the next decade. Estimates of domestic crude oil availability were made, including quantity and disposition of Alaskan North Slope and offshore fields. Also, estimates of worldwide crude oil production and disposition were made, taking into account future product demand in Europe, Japan and the United States in terms of product type and sulfur level requirements. Likely production rates from the North Sea, OPEC countries, and Far East countries, including China, were included in this analysis, as was the likely availability of non-oil energy sources such as coal and nuclear power. When more than one future scenario for the next decade was likely, sensitivity studies were included in the current program to determine the effect of this uncertainty on the study results.

Since the cost of controlling the sulfur content of unleaded gasoline depends directly upon the demand for unleaded gasoline and indirectly upon the demand for other petroleum products, a separate forecast was made of petroleum product supply/demand for the next decade. This forecast included an evaluation of the demand for products by individual end-use sector, including the effects of non-petroleum energy sources, conservation, import levels, expanded petrochemical demand for certain products, and the future course of governmental regulation in improving energy self-sufficiency for the U.S. Because of the uncertainties in this area, sensitivity studies were included to ensure that these uncertainties did not influence study results.

The impact of any potential regulation also depends upon certain key product specifications on the primary product under control as well as other major refinery products. Present and possible future octane requirements on unleaded gasoline were evaluated. Projections were also made of the future sulfur level requirements of residual fuel oil. To assist in this evaluation, field interviews were conducted with East Coast utilities, accounting for over 90% of the utility fuel oil consumption on the East Coast. Again, certain sensitivity studies were required to define the effects of uncertainties in projections on the study results.

Several other significant assumptions were made in the execution of this program, which are discussed in detail in the following report.

C. CONCLUSIONS

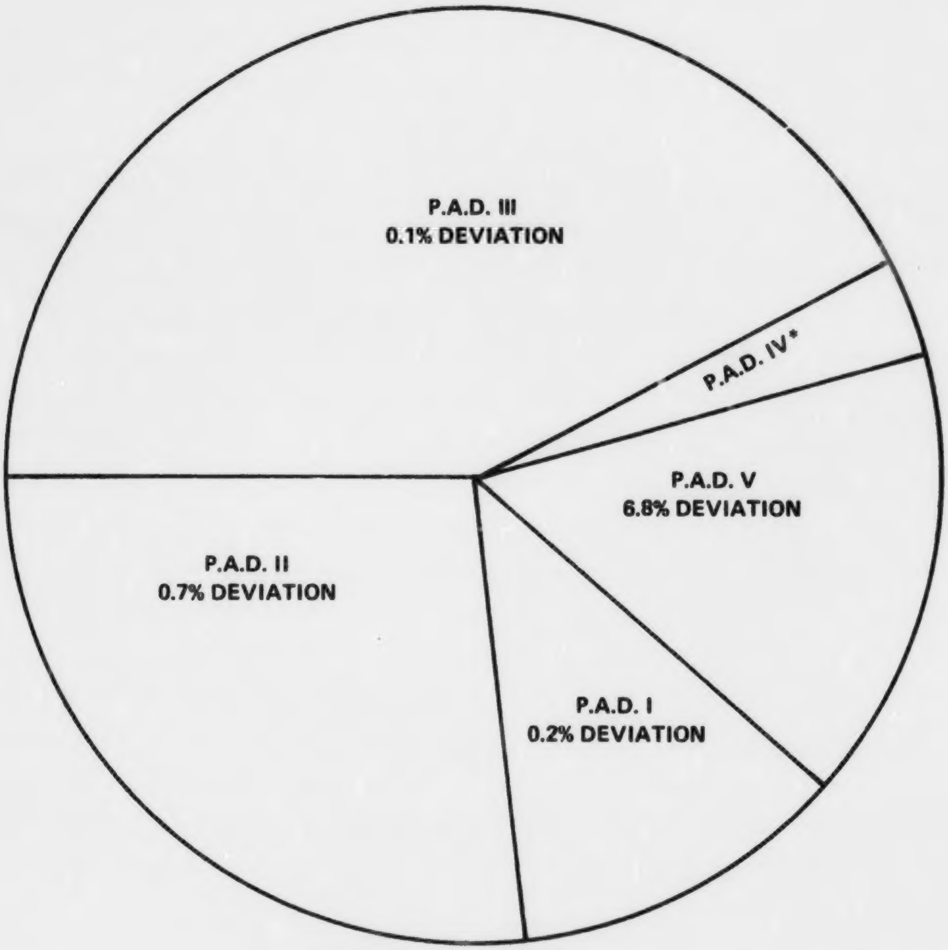
1. Calibration Summary

In order to simulate the existing U.S. petroleum industry, six cluster models were developed to describe the regional characteristics of the refining industry and the processing configurations typical of the industry. Each of these six cluster models represented a cluster of three similar, existing refineries in the United States.

A critical component of the model development was to ensure that these models effectively represented the refineries as well as the section of the United States containing the refineries. Therefore, an extensive calibration effort was undertaken by Arthur D. Little, Inc., in collaboration with representatives of the Environmental Protection Agency (EPA) and a task force of the American Petroleum Institute/National Petroleum Refiners Association.

Data on raw material intake, fuel consumption, and product outturns for each of the refinery clusters and for regions of the U.S. containing these clusters were furnished by the Bureau of Mines. Proprietary operating data on these refineries were compiled and combined for each cluster by representatives of the EPA. Processing information was obtained from sources in the petroleum industry. Using this processing information the individual cluster models were run on the computer, and compared with the industry data. This task was continued until each cluster model was calibrated with the industry data.

The results of these calibrated cluster models were then scaled up to determine the accuracy with which the refining districts in the U.S. were described. In Figure 1 is shown the deviation of the model predictions from the total raw material intake for the several Petroleum Allocation for Defense (PAD) districts in the U.S. As noted therein, the maximum deviation was 6.8% (PAD V), and the deviation from the total U.S. raw material intake was 1.0%. PAD IV (less than 5% of U.S. crude oil capacity) was not simulated by a cluster model, but was included in the scale up method. Thus, as a result of this extensive calibration effort, the cluster models demonstrate an excellent ability to simulate the existing U.S. petroleum refining industry, using processing information describing individual refinery units.



U.S. Total Deviation = 1%
*Not simulated, but included in scale-up

FIGURE 1. AGREEMENT OF MODEL PREDICTION WITH 1973 B.O.M. TOTAL REFINERY RAW MATERIAL INTAKE DATA (Area on chart represents percentage of total U.S. refinery intake by P.A.D. District)

2. Qualitative Study Results

Gasolines produced in the U.S. today have an average sulfur level of around 400 ppm. The primary source of this sulfur is gasoline produced from the fluid catalytic cracking (FCC) unit. Although gasolines from coking units tend to have higher sulfur levels than FCC gasolines, the volume of coker gasoline produced is significantly less than the volume of FCC gasolines produced.

If refiners are to manufacture unleaded gasolines with sulfur levels of 100 ppm or 50 ppm, they must reduce the sulfur level of the FCC gasoline. The choices available are desulfurization of the feed to the FCC unit or direct desulfurization of FCC gasoline. Desulfurization of FCC feed often cannot remove desired amounts of sulfur if the sulfur level of the FCC feed is high, whereas direct desulfurization of FCC gasoline can remove virtually all of the sulfur. However, FCC feed desulfurization does allow higher conversion and improved product selectivity in the FCC unit. The octane number of FCC gasolines tends to increase slightly as conversion increases and this is another benefit of FCC feed desulfurization. Direct desulfurization of FCC gasoline, however, results in a reduction of the clear octane levels of this gasoline component as a result of the saturation of higher octane olefinic compounds into lower octane paraffinic compounds (associated with the desulfurization process). This results in increased requirements for catalytic reforming to make up the lost octane. Therefore, the preferred route to manufacture low sulfur, unleaded gasoline is by FCC feed desulfurization if this can achieve the desired sulfur level in the unleaded gasoline pool.

The results of this study indicate that those refiners who process very high sulfur crude oils will probably have to use the direct desulfurization of FCC gasoline to produce unleaded gasolines with a sulfur level of 100 ppm or 50 ppm. The threshold level of crude oil sulfur which differentiates between the two choices is not clearly defined since it will depend on the amount of FCC and coking capacity in any particular refinery. Of the six cluster models studied, only the Large Midwest cluster required direct desulfurization of FCC gasoline to manufacture 100 ppm gasoline and both the Large Midwest and Texas Gulf clusters required this for the manufacture of 50 ppm gasoline.

3. Economic Penalties

The economic impact by 1985 on the U.S. refining industry for the manufacture of low sulfur unleaded gasolines is shown in Table 1. This shows estimates of the capital requirements to be 2.6 billion dollars for the manufacture of 100 ppm gasoline and 4.0 billion dollars for the manufacture of 50 ppm gasoline. These capital estimates are on a first quarter 1975 basis and the final capital requirements are expected to be of the order of 7.0 and 10.4 billion dollars based on the timing of the investments and forecasted inflation rates in refinery process construction. The additional cost to the U.S. refining industry is estimated to be 0.78 cents per gallon of unleaded gasoline for 100 ppm gasoline and 1.63 cents per gallon of gasoline for 50 ppm gasoline based on first quarter 1975 costs, relative to unleaded gasoline. This includes an annual capital charge of 25% of the total additional capital required.

Figure 2 shows the estimates of the economic penalty in 1977, 1980 and 1985, and breaks down the cost into capital charge, operating costs and crude and product penalties. This illustrates a lower cost in 1977 and 1980 because high sulfur gasoline components have to some extent been blended into leaded grades of gasolines. However, by 1985 when 100% unleaded gasoline production was assumed, the estimated full cost of sulfur removal emerges.

These estimates have been based on the scale up of the results from eight different refinery LP models which blended the low sulfur gasoline to exactly 100 ppm and 50 ppm. They therefore represent estimates of the economic penalties for manufacturing gasolines with average sulfur levels of 100 ppm and 50 ppm. They do not represent the penalties for manufacturing gasolines with maximum specification of 100 ppm and 50 ppm. The penalties for manufacturing gasolines with maximum specifications of 100 ppm and 50 ppm have been estimated assuming that average blending targets of 80 ppm and 40 ppm would be required to ensure the maximum specification is met. The estimated capital requirements increase to 3.2 and 4.4 billion dollars and the economic penalties relative to unleaded gasoline increase to 1.12 and 1.99 cents per gallon of gasoline for the manufacture of gasoline meeting 100 ppm and 50 ppm maximum specifications, respectively.

Table 1. ECONOMIC PENALTIES FOR THE MANUFACTURE OF LOW SULFUR UNLEADED GASOLINE BY 1985

	100 PPM (average level) gasoline	50 PPM (average level) gasoline
Capital required — billions of dollars		
Non-inflated (1Q 1975 basis)	2.6	4.0
Inflated	7.0	10.4
Total economic penalty relative to unleaded gasoline		
Cents per gallon of low sulfur unleaded gasoline (1Q 1975 basis)	0.78	1.63

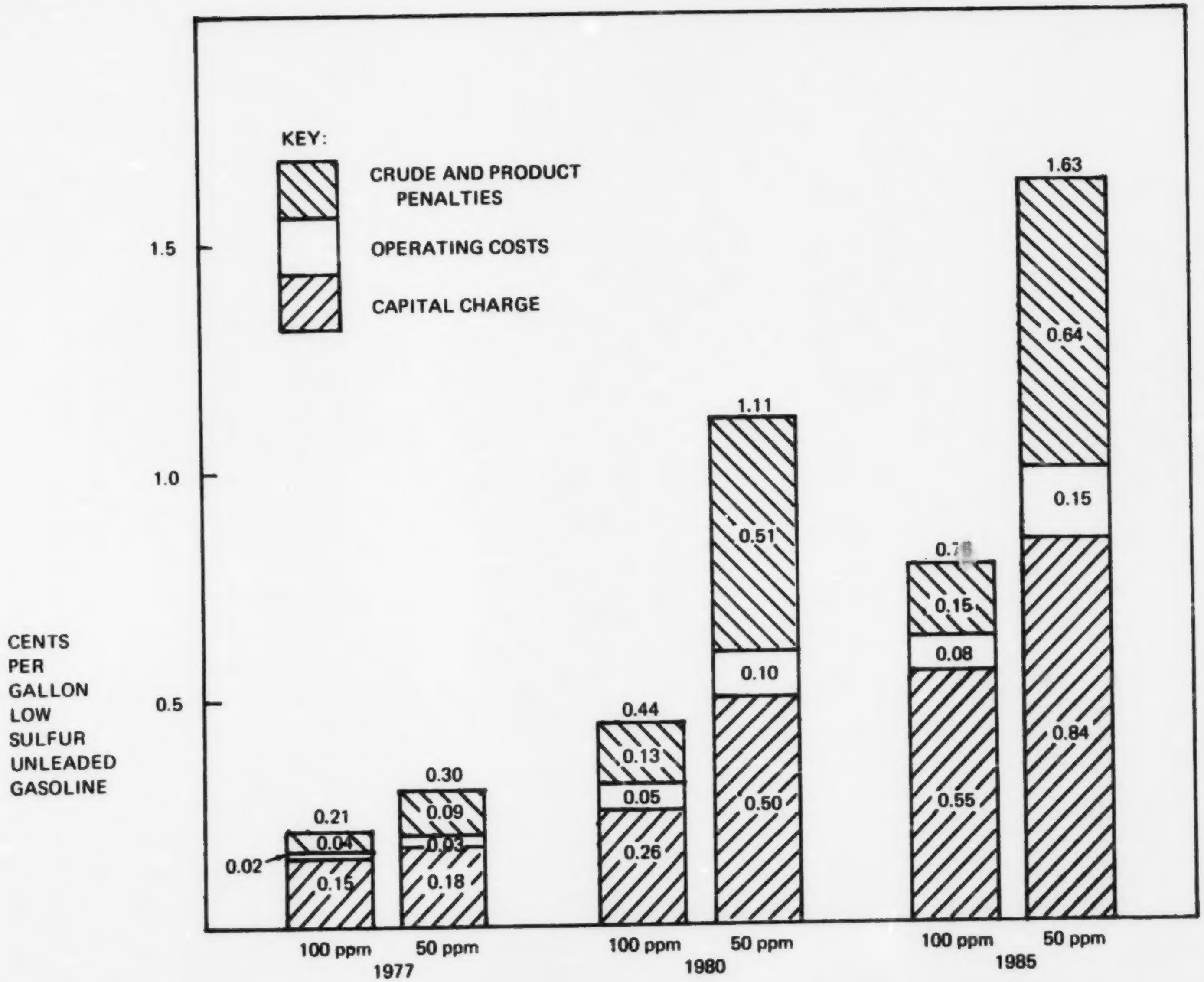


FIGURE 2 ECONOMIC PENALTY FOR THE PRODUCTION OF LOW SULFUR UNLEADED GASOLINE RELATIVE TO UNLEADED GASOLINE

4. Crude Oil and Energy Penalties

The estimates of the crude oil and energy penalties for manufacturing low sulfur unleaded gasoline are shown in Table 2. Relative to unleaded gasoline, by 1985, it is estimated that the U.S. refining industry will have to process additional crude oil approaching 80,000 barrels per day to manufacture 100 ppm unleaded gasoline and nearly 350,000 barrels per day to manufacture 50 ppm unleaded gasoline. However, the industry would produce more LPG as a result of manufacturing low sulfur gasoline which would partially offset this crude oil penalty. The net energy penalties by 1985 are estimated to be 42,000 barrels per calendar day of fuel oil equivalent for the manufacture of 100 ppm gasoline and 160,000 barrels per calendar day for 50 ppm gasoline.

5. Sensitivity Studies

The manufacture of low sulfur, unleaded gasoline must be achieved by reducing the sulfur levels of FCC gasolines. The sulfur levels in FCC gasolines are themselves dependent on the sulfur level in the feed to the FCC unit. However, the relationship between FCC feed sulfur level and FCC gasoline sulfur level, differs considerably, depending on the source of the FCC feed. To date, limited data are available on this relationship, which is critical in determining the impact of manufacturing low sulfur gasolines. A recently published report analyzed this relationship for several FCC feedstocks and these relationships were used in calculating FCC gasoline sulfur levels in the present study. However, applying the results of such a study of a limited number of feedstocks to the whole of the U.S. refining industry obviously has its shortcomings. Therefore, a sensitivity study was done using different assumptions on FCC gasoline sulfur levels. In the base study the percentage of the FCC feed sulfur that was assumed to be present in FCC gasoline was approximately 4.7% (it varied from a low of 3.1% to a high of 10.1%). The sensitivity study examined the impact of assuming that FCC gasolines contained an average of 7.0% of the feed sulfur.

The results of the sensitivity study are shown in Table 3. These show a significant increase in the capital investment requirements and in the economic penalty of 25% to 35%.

Table 2. CRUDE OIL AND ENERGY PENALTIES FOR THE MANUFACTURE OF LOW SULFUR UNLEADED GASOLINE [a]

	1977	1980	1985
100 PPM gasoline			
Additional crude oil required thousands barrels per calendar day	6.9	27.8	78.7
Additional LPG produced thousands barrels per calendar day	5.8	13.1	53.2
Net energy penalty thousands barrels per calendar day of fuel oil equivalent	3.3	18.1	42.1
50 PPM gasoline			
Additional crude oil required thousands barrels per calendar day	10.9	88.7	343.2
Additional LPG produced thousands barrels per calendar day	5.7	23.0	244.3
Net energy penalty thousands barrels per calendar day of fuel oil equivalent	7.1	68.3	160.2

[a] Relative to unleaded gasoline

Table 3. EFFECT OF INCREASED FCC GASOLINE SULFUR LEVELS ON THE 1985 ECONOMIC PENALTY FOR MANUFACTURING LOW SULFUR, UNLEADED GASOLINE

	100 PPM Gasoline		50 PPM Gasoline	
	Base Case	Sensitivity Case	Base Case	Sensitivity Case
FCC sulfur distribution	4.7% av	7.0%	4.7% av	7.0%
Capital requirement billions dollars (1Q 1975 basis)	2.6	3.3	4.0	5.5
Economic penalty cents per gallon low sulfur gasoline (relative to unleaded gasoline) (1Q 1975 basis)	0.78	1.02	1.63	2.16

6. Other Major Implications

The choice of six different cluster models to represent the existing U.S. refining industry was made to provide a reasonable representation of the different types of refineries operating today. Over 80% of the U.S. refining capacity has been represented in the cluster models. However, no cluster model was constructed which could be considered representative of the small refiner (less than 50,000 barrels per day), nor would such a model be sufficient to a study of the impact on small refiners. These refiners represent less than 20% of total U.S. refining capacity and any understatement of their penalties will not significantly affect the overall conclusions. However, the production of low sulfur gasolines could have a significant impact on the smaller refiner. He may not have the wide choice of blending components available to the larger refiners and little, if any, existing treatment equipment. Because of the economies of scale the unit cost to the small refiner of manufacturing low sulfur, unleaded gasoline could be appreciably higher than those indicated in this study. This could have a significant impact on the competitive structure of the refining industry.

An alternative method of direct desulfurization of catalytic cracker gasoline was examined, wherein the FCC gasoline was split and only the heavy fraction desulfurized. The limited data available suggests that this method would remove 70% to 80% of the sulfur in the FCC gasoline. At the same time it would avoid having to hydrotreat the lighter, olefinic fractions in the FCC gasoline, which result in substantial loss of octane. Since the data available on sulfur distribution within FCC gasolines for various crude oil types is limited, it is difficult to suggest an optimal scheme which would achieve the correct balance between sulfur removal and octane loss. However, refiners who must desulfurize FCC gasolines (because FCC feed desulfurization will not meet the required sulfur level) will undoubtedly consider this alternative method of desulfurizing FCC gasolines. The more conservative approach of desulfurizing the whole FCC gasoline with subsequently large octane losses has been assumed in the study because of lack of available data on the alternative method. The capital, economic, and energy penalties estimated for the manufacture of low sulfur gasoline therefore may be conservative, since they may be reduced somewhat by this alternative method of FCC gasoline desulfurization.

D. RECOMMENDATIONS FOR FURTHER ACTION

In order to assess more fully the impact of manufacturing low sulfur, unleaded gasoline, several areas are worthy of more consideration than possible with this study:

1. The relationship between FCC feed sulfur and FCC product sulfur level should be refined, particularly for gas oil derived from North Slope crude oil. With this information, additional model runs could be undertaken.
2. Similar information should be ascertained for delayed coking units.
3. The distribution of sulfur and the octane loss upon desulfurization of FCC gasoline fractions should be refined for the crude oil types in the model simulation. With this information, additional model runs could be undertaken to estimate industry impact using selective desulfurization of FCC gasoline fractions.
4. The impact of sulfur control should be assessed more fully for the small refiners processing less than 50,000 barrels per day. Such studies should examine the economic impact on the refiners as well as the likely effect on the competitive structure of the industry.
5. Costs of distribution and marketing of low sulfur, unleaded gasoline should be assessed to determine if they differ from analogous costs of unleaded gasoline.

II. STUDY BASIS

A. APPROACH

The objective of this study is to determine the impact on the petroleum refining industry of a possible Environmental Protection Agency (EPA) regulation requiring the reduction of sulfur content in unleaded gasoline to either 100 ppm or 50 ppm, taking into consideration limitations of present refinery configuration and potential grassroots refinery construction. Since the processing interactions in any single refinery are exceedingly complex, and indeed even more complex for the industry as a whole, such an assessment of the impact of this potential regulation could be addressed by two possible approaches.

First, a survey could be conducted by sending out a questionnaire[1,2] to individual refiners across the country, requesting an assessment of their individual costs for meeting the potential regulation. The results could then be composited to define the cost to the industry. Although this is a valid approach, it is often difficult to determine if the specific regulation is being interpreted equivalently by all refiners across the country, if they are using a similar analytical procedure, if they are using the most efficient means of meeting the regulation, and if they are using a common basis for cost estimation. This method, however, does have the decided attribute of allowing each individual refiner to assess his unique problems in meeting the regulation.

An alternative approach, used in the present study, is to simulate the U.S. refining industry using computer models. Computer simulation of individual refineries is well-known and has been practiced for over a decade. Such a simulation normally utilizes a linear programming (L.P.) model to represent the individual process units and the process interactions of the refinery. In the present study, however, simulation of a single refinery is not sufficient in that no single refinery can be said to represent the entire refining industry. Therefore, eight computer models were used simulating individual refineries which, when composited, would be typical of the industry as a whole.

In the use of any L.P. model it is necessary to define the types of crude oils available to the model, the individual process yields, the streams that can be used to connect the processes, and the products produced from the refinery. The model then uses an optimization algorithm to select the optimal combination of process units meeting the objective of the study. If all product prices are given as input to the model, the model will select that set of product outturns and processing configurations which will maximize profit derived from the complex. However, this method of L.P. optimization may not assure that the quantities of products being produced from the complex meet the product demands of the region being served by that refinery. If this happened in the actual operation of the refinery, market forces would increase the prices of those products in short supply and decrease those in excess supply, so that the entire refinery operation would be adjusted with the product outturns just meeting the product demands. In a computer simulation of a refining industry, however, it is very difficult to predict those product prices which are required to match the product outturns with the market demands. In the present studies, an alternate approach was taken, wherein the product outturns from the refinery were fixed in order to meet the projected product demands imposed upon the U.S. refining industry. Therefore, the L.P. algorithm selected a set of processing configurations which allowed this specified product demand to be met at minimum cost. However, it is necessary that the problem being optimized be carefully constructed such that the real-world constraints on the industry in meeting these minimum cost objectives would be met, allowing a realistic simulation of the operation of the industry. The definition and inclusion of these constraints is an exceedingly important component of a study of the impact of any potential regulation on the industry. This activity was greatly benefited by the results of a Federal Energy Administration/National Petroleum Refiners Association conference on refining industry modeling.[3]

In order to meet the constraints which would be imposed upon the refining industry, comprised of nearly 300 individual refineries spread throughout the United States, Arthur D. Little, Inc. (ADL), representatives of the EPA, and a task force comprised of representatives of the American Petroleum Institute and the National Petroleum Refiners Association selected three refineries in each of six geographic regions to simulate the existing U.S. refining industry. These six refinery models (cluster models) were constructed and calibrated[4] against the three actual refineries in each region to ensure that the product blend flexibility and the processing configuration flexibility did not exceed that available to these refineries. In simulating these existing refineries over the next decade, the crude run for the individual cluster models was not allowed to exceed the crude capacity for those refineries being simulated. All new crude capacity required to meet increased product demand was met by the construction of new, grassroots refineries.

In the construction of new grassroots refineries, the refining industry East of the Rockies was represented by a class of refineries feeding crude oil typical of imported oil likely to be available in the coming decade. Another simulation model was developed for grassroots refineries to be constructed West of the Rockies, feeding Alaskan North Slope crude oil. The product outturn from all of the existing refineries (cluster models) and the new refinery installations (grassroots models) was then composited to ensure that the overall product demand for the United States refining industry was met.

It is also important that the major products of the models meet appropriate quality constraints typical of the product quality demand by the market place over the next decade. In some cases these product quality definitions are implicit in the EPA regulation under study, for example the constraint that unleaded motor gasoline contain no more than 100 ppm sulfur. In other cases, projections of future product quality requirements are necessary in order that the study be a realistic representation of the industry over the next decade. Of particular importance in this regard is the sulfur level of the residual fuel oil being produced by the industry. Separate studies were made of these product qualities to determine the likely levels associated with the industry over the next decade, discussed in the planning assumptions for the study.

The impact upon the refining industry which is evaluated in the present study includes: the capital investment requirements for the refinery to meet the potential regulation, the composite capital charge and operating cost expressed per gallon of low sulfur unleaded gasoline, the crude oil penalty, and the net energy penalty associated with the regulation (including byproducts which have an energy value).

There are other considerations important to the determination of the impact of the regulation. These other considerations were beyond the scope of the study and have not been evaluated in detail. For example, the study determines the capital outlay required to meet the potential regulation by the industry. However, it is likely that, for many of the small refiners in the country, the projected capital outlay will require financing that may not be available to them at the present time. The availability of capital required by the potential regulation is specifically beyond the scope of this study, as was the impact of the regulation on the competitive structure of the industry. Also, some of the processing requirements needed to meet the regulation require significant construction of heavy-walled vessels. The impact of the regulations upon the construction industry, including the fabricators and vendors, is also not considered to be within the scope of the present study. The impact of the distribution and marketing requirement of the possible regulation is also not addressed herein.

B. CASE DEFINITIONS

The cluster model approach used in the present study of the possible regulation requiring reduction of the sulfur content of unleaded gasoline was also used in two other studies, which were conducted simultaneously: (1) a study of a possible regulation requiring reduction of gaseous sulfur-oxide (SO_x) emissions from petroleum refineries, and (2) reassessment of promulgated regulations relating to lead additive content of gasoline (Federal Register, December 6, 1973; January 10, 1973). To conduct these studies, six scenarios were created as possible modes of operation of the refining industry, each of which were evaluated for 1977, 1980 and 1985. These scenarios are:

Scenario A: Unregulated operation and expansion of refining industry to meet projected petroleum product demand over the next decade.

Scenario B: Manufacture of unleaded gasoline to meet projected demands, with no lead restriction on the total gasoline pool or sulfur restrictions on unleaded gasoline.

Scenario C: Phased reduction in the lead additive content of the total gasoline pool, with no sulfur restrictions on unleaded gasoline.

Scenario D: Manufacture of unleaded gasoline with a maximum of 100 ppm sulfur, while reducing the lead content of the gasoline pool.

Scenario E: Manufacture of unleaded gasoline with a maximum of 50 ppm sulfur, while reducing the lead content of the gasoline pool.

Scenario F: Reduction of refinery gaseous sulfur-oxide emissions by restrictions on the sulfur content of the refinery fuel, by restriction of fluid catalytic cracker plant emissions, and by restriction of sulfur recovery (Claus) plant emissions, while meeting all the requirements of Scenario C.

The complete definition of the computer cases to be run under these several scenarios requires assumptions of crude intakes to the U.S. refinery industry, processing configurations, and product outturns and qualities. However, other planning assumptions which have a possibility of occurring over the next decade were also considered. Variations in these assumptions were investigated by a series of parametric runs, wherein the assumptions were modified, one at a time, to reassess the impact on the industry. The scope of these parametric studies is summarized in Table 4.

For the study of lead in gasoline (Scenarios A, B, and C) five major parametric studies were undertaken. A basic premise of the study in the base case is that unleaded gasoline will be produced by the industry meeting 92 Research Octane Number (RON) and 84 Motor Octane Number (MON). These specifications were set one octane number higher than the minimum required by the EPA regulation to allow for refinery blending margin. To evaluate the effect of producing even higher octane unleaded gasoline, two parametric runs were conducted as summarized in Table 4.

Projections of the future sulfur content of residual fuel oil consumed in the United States are between 1.1 and 1.4%. As a base planning assumption, it was considered that the residual fuel oil

Table 4 . PARAMETRIC STUDIES

Lead in gasoline	Low sulfur unleaded gasoline	Refinery sulfur oxide emissions
Unleaded gasoline RON/MON = 93/85	Residual fuel oil Sulfur level projection	Variation in imported crude slate
Unleaded gasoline RON/MON = 94/86	Variation in imported crude slate	Residual fuel oil, sulfur level projection
Residual fuel oil sulfur level projection	Sulfur distribution around FCC unit	Stack gas scrubbing
Variation in product demand	Method of FCC gasoline desulfurization	
Variation in imported crude slate		

being consumed in the United States would have a sulfur content of approximately 1.3%. Since this requires extensive desulfurization in the new grass-roots refinery facilities, an additional parametric run at 1.1% sulfur was conducted to ensure that study results were not being unduly influenced by this assumption. It must be emphasized, of course, that the average sulfur level of the fuel oil consumed by all sectors in the United States is below even 1.1%, because of significant levels of imports of low-sulfur fuel oil into the United States over the next decade.

In the base case studies defined by the above scenarios, it was assumed that all petroleum products would grow at a level of 2% per annum. This is a reasonable estimate of the growth of all petroleum products.[5] However, it is likely that each individual product will not grow at 2% per annum, so parametric runs were undertaken to evaluate the impact of growth rates for petroleum products other than 2%.

Arthur D. Little, Inc., has conducted a worldwide survey of crude oil production and disposition to the various refining regions. This indicated that two alternatives might be considered for the imported crude oil into the East Coast region: (1) the imported oil could be of relatively high sulfur content characteristic of Arabian crudes, or (2) the imported oil may be of relatively lower sulfur level, characteristic of Nigerian crudes. There is great uncertainty as to the demand and availability of various crude oils in the United States[6] and the ultimate selection of crude oils would depend upon this uncertain demand as well as a variety of political factors. The base case under the above scenarios assumed a predominately Arabian-type imported oil. An additional parametric run was made with a lower-sulfur oil being characteristic of the imported oil.

In the program to evaluate the impact of a reduction of sulfur levels in unleaded gasoline a similar set of parametric studies were required. As indicated in Table 4, projections of the refinery residual fuel oil sulfur level and variations in imported crude slate, discussed above, were also considered.

The attention of the refinery industry to sulfur levels in gasoline in general has been minimal over the last few decades because of the relative lack of importance of sulfur level as a product specification. Therefore, there is limited information available regarding the sulfur level of some of the high sulfur gasoline blend components from the various refinery processes under various conditions of operation. One of the most critical refinery units with regard to the sulfur content of unleaded gasoline is the fluid catalytic cracker (FCC). Sulfur levels of the products from the FCC unit were obtained by consideration of available data on the FCC unit, feeding various types of gas oil and under various types of operating conditions. However, since there are uncertainties in the sulfur content of gasoline from FCC units, a parametric run was instituted to evaluate the impact of higher levels of sulfur in the FCC gasoline than was assumed in the base case scenarios above. This, then, led to a range of potential impact on the petroleum industry in consideration of both the base case sulfur level as well as the new parametric case sulfur level.

Because the interest in the sulfur content of FCC gasoline has been recent, the most efficient means of desulfurizing FCC gasoline has not been determined. One attractive method of reducing the sulfur level in the FCC gasoline is by hydrotreating the FCC feedstock. Another method is to directly desulfurize FCC gasoline, requiring further reforming of the desulfurized product. However, laboratory data has shown that the sulfur distribution in FCC gasoline is heavily weighted toward the heavy gasoline component. This suggests that only the heavy gasoline component need be directly desulfurized, with the light FCC gasoline component going directly into the gasoline blend stock. This method of desulfurization of FCC gasoline could potentially reduce the impact on the refining industry of meeting the possible sulfur regulation. Consequently, one parametric run was made to determine the possible savings from this method of desulfurizing FCC gasoline.

In the study of the impact of proposed regulations reducing the sulfur oxide emissions from refineries, several parametric studies were also undertaken. Variations in the sulfur level of imported crude slate and sulfur level of the product residual fuel oil are clearly of potential importance in the impact of regulations reducing refinery sulfur oxide emissions. These parametric studies, discussed above, were included in this particular task.

It is felt that the most likely means by which the refining industry will meet possible regulations regarding sulfur oxide emissions is to control the sulfur level of the refinery fuel system, to desulfurize the FCC feedstock (thereby reducing FCC regenerator sulfur oxide emissions), and to add tailgas cleanup processes to the sulfur recovery unit (Claus process). However, it is also possible that the emissions from the FCC unit and the refinery fuel system could be reduced by the utilization of stack gas scrubbing techniques, under extensive study for possible application in the utility industry. Consequently, parametric runs were undertaken to determine if the total impact of the regulations reducing sulfur oxide emissions could be diminished by application of the utility-based stack gas scrubbing techniques.

The present report deals with the impact only of the possible regulation reducing the sulfur content of unleaded gasoline. Companion reports[7,8] have been produced which address the impact of the promulgated regulations for lead additives in gasoline and the consequences of a possible regulation to reduce sulfur oxide emissions from the petroleum refining industry. All further discussions in the present report will address the possible sulfur reduction regulation for unleaded gasoline.

C. PLANNING ASSUMPTIONS

This subsection defines the methodology used in developing planning assumptions required for the present study, as well as identifying the primary assumptions used. Because of the amount of detail required in presenting these planning assumptions, only an outline of this information will be presented below. Additional detail on all of the topics discussed is presented in the appendices of Volume II of this report.

1. Crude Slate Projections

Projection of the crude slate available for the domestic U.S. refinery industry depends upon a complex interaction of the production capability of domestic U.S. crudes, the demand for petroleum products, the influence of alternate energy sources within the U.S., the worldwide availability of crude oils and the demand worldwide for these same international crude oils. Arthur D. Little, Inc., investigated the worldwide oil supply by consideration of production potential from the North Sea, OPEC countries, the United States, South America and the socialist countries. Superimposed upon this production potential was the investigation of world oil demand forecasts and product demand forecasts for the major refining and consuming areas, i.e., the U.S.A., the Caribbean, Western Europe, and Japan. These product demand forecasts indicated, for example, a significant lightening of the future product demand barrel in Europe, a similar but less significant change in Japan, and virtually no change in the relative proportions of demand within the United States. This led to a projection that there would be a tendency for heavier crudes, including Nigerian, to be attracted to the U.S.A. and lighter crudes, including Algerian, to be attracted to Europe. Crude oil demand for Japan included both imports from the OPEC countries as well as probable production of Chinese crude oil. In addition, the demand for sulfur content of various products was investigated, allowing an assessment of the likely movements of crude oils of various sulfur levels into the various consuming regions in the world. The assessment of all these factors in combination allowed projections of the disposition of the various crude oils to the various refining regions.

Superimposed upon any such projection of the availability of crude oils to the United States must be an evaluation of the proportion of the U.S. refineries which can run sweet and sour crudes. Obviously, a refinery designed for sweet crude operation can be redesigned to allow operation with sour crudes, but this would be accomplished only if there is sufficient price driving force between the sweet and sour crudes. For example, the NPRA has evaluated the availability of refineries which depend upon low-sulfur crude oil and have indicated that 9% of the refining capacity would be unavailable if the industry were forced to substitute high-sulfur crude oil for 20% of the sweet crude they are now running.[9]

After consideration of all of these factors the planning assumption for the crude oil to be run by the U.S. refining industry over the next decade is summarized in Table 5. Additional detail on the crude oils run to the refining industry in 1973 as well as the assumptions made in reducing this number of crude oils to a smaller but still descriptive level is contained in Appendices F and I. Additional detail on the methodology utilized to obtain the projected crude run shown in Table 5 is presented in Appendix A.

Table 5. U.S. REFINERY CRUDE RUN
(millions of barrels per calendar day)

	1977	1980	1985
Domestic			
Alaskan North Slope	–	1.3	1.5
Other	9.4	9.0	8.5
Subtotal domestic	9.4	10.3	10.0
Domestic, percent of total	70.7%	70.1%	61.0%
Imported			
Arabian	2.1	2.7	4.0
African	0.8	1.3	2.0
South American	0.5	0.4	0.4
Other	0.5	–	–
Subtotal imported	3.9	4.4	6.4
Imported, percent of total	29.3%	29.9%	39.0%
Total crude run	13.3	14.7	16.4

In addition to the overall crude slate to be processed by the U.S. refining industry, a breakdown between the crudes being processed by existing refineries and those to be processed by new grassroots refineries over the next decade must be specified. As described below, the existing U.S. industry is simulated by means of six cluster models. The cluster models process all available domestic crude over the time span of the next decade and use imported crude as required to meet overall product demand. In the base case, these imported crudes were assumed to be comprised predominantly of Arabian Light crude oil. The grassroots model on the West Coast processes only Alaskan North Slope crude oil, because projections indicate an ample supply of North Slope crude oil to meet the demands of PAD District V. Note, however, that although some published reports[6] indicate an ample supply of North Slope crude oil for PAD District V (even leading to planning for a pipeline transport of excess North Slope oil to the Midcontinent), there is not a consensus among the major U.S. refiners as to whether the North Slope crude will be sufficient to exceed the petroleum product demand in District V.

The crude oil to be processed in the new grassroots refineries East of the Rockies is assumed to be imported oil, predominantly Arabian Light crude oil. However, as noted above, a parametric run was made to investigate the impact of importation of lower sulfur crude oils, such as Nigerian-type oils. This parametric run would also be indicative of the result of the introduction of Alaskan North Slope crude oil into the Midcontinent, used in new grassroots refinery construction East of the Rockies.

2. U.S. Supply/Demand Projections

Prior to 1973, forecasting the oil demand in the United States was a straightforward exercise, involving the application of historically determined growth rates to base year consumption data. However, the pattern of continuous growth was interrupted by increases in foreign and domestic oil prices, the oil embargo, and a period of economic recession.

The general approach which has been used by ADL in product demand forecasting is to conduct an indepth analysis of total energy requirements by individual end-uses, which are then matched with projections of supplies of basic energy sources, including oil, gas, coal, nuclear and hydroelectric power. Because of the stimulus of high oil prices and considerations of security of supply, non-oil energy supplies are developed as rapidly as possible, limited only by technical, environmental, governmental, and resource considerations on the one hand, and by end-use considerations on the other, such as the nuclear contribution being limited to the base load electric power generation. The availability of non-oil energy sources are also evaluated in the light of the recent declines of United States natural gas production, potential environmental constraints on exploitation of coal reserves, inflation-caused reappraisal of the capital intensive new energy forms such as oil shales, and failure to meet targets for nuclear generation capacity. Furthermore, the product demands incorporate recent changes in the structure of energy use within end-use sectors, such as increased electricity consumption in the domestic sector and an increased use of oil as petrochemical feed stock. Also included is the effect of energy conservation. Of course, the impact of energy conservation is difficult to assess from recent product demand data because of the simultaneous occurrence of economic recession, mild winters, and high oil prices.

In the current study the demand forecast for the United States refining industry was obtained by two different approaches. To facilitate the task of combining the demand forecast with the scale up of the cluster models (Appendix G), one simplistic forecasting approach was utilized which led to a growth rate of 2% per annum for all products from the domestic refining industry. However, to ensure that the study results were not unduly influenced by this simplistic approach, parametric runs were undertaken to evaluate the affect of a more sophisticated forecasting technique. Each of these forecasting techniques will be discussed in summary form here, while additional information of a detailed nature is presented in Appendix B.

a. Uniform Product Growth at 2% Per Annum -

Since the demand forecasts are intended simply to identify differences in refining requirements among the six scenarios, the actual demand forecast for each product may be relatively unimportant. Therefore, the methodology, discussed in additional detail in Appendix B, contains three key simplifying assumptions: (1) demand for all products grows at one uniform rate of 2% per annum between 1975 and 1985; (2) demand growth occurs in equal increments throughout this forecasting period; and (3) product imports are maintained at 1973 levels.

From the base year, 1973, product demand was forecast to realize zero growth over 1974 and 1975, and average 2% per annum thereafter. Beyond 1975, published projections of oil demand growth rate range between 1% and 3.5% per annum, depending upon assumptions regarding oil prices, consumer price sensitivity, conservation incentives, the availability of alternate energy forms, and U.S. government policy. An estimate of 2% average annual growth was selected to reflect generally slower than historical growth rates resulting from higher oil prices, but assuming some optimism regarding the future economic growth of the country.

It is not likely that this demand forecast will closely approximate the real growth of petroleum products over the next decade; however, this was demonstrated in the present study to be an adequate assumption of this product growth rate. To arrive at this conclusion, a parametric run was made utilizing more detailed evaluations of product demand growth, the methodology for which is discussed below.

b. Non-Uniform Petroleum Product Growth Rates -

In this more sophisticated projection of product demand growth rate, two sets of assumptions were used to develop a definitive range of energy supply/demand balances. In one case, economic growth was assumed to be somewhat slower than historical rates, but high enough to permit a rising standard of living. Higher energy prices alone (but not governmental action) are assumed to result in consumer energy conservation. Likewise higher energy prices provide the incentive for the development of domestic energy resources. A second case was defined in which economic and total energy growth fall further off historic rates as a result of both strong governmental action and higher energy prices. Government action in the form of conservation incentives, selective taxes on oil, import tariffs on oil, etc., is taken to enhance the effects of higher prices in dampening demand and stimulating the development of domestic resources.

In both of these categories, coal production and consumption, which have declined in recent years, are expected to be rejuvenated as a result of higher energy prices. After development of the coal industry, production capacity will no longer be such a severe limitation on coal consumption after 1980. Natural gas is assumed to be supply-constrained throughout the forecast period, as production from the contiguous United States fields continues to decline and is not offset by volumes from Alaskan sources until very late in the forecast period. Nuclear power is expected to be the most rapidly growing primary energy form, showing 25- to 30-fold increase over the forecast period. Nonconventional energy sources, such as solar, are not expected to play a significant role during the time frame of this forecast.

The demand for energy was developed by breaking down the total energy consumption into demand by various end-use sectors (e.g., transportation, industrial, residential/commercial, etc.). At the end-use sector level, the historical growth trends in energy consumption were identified and then modified in line with the basic assumptions described above. The modification of historic growth rates took into account our expectations of the impact of consumer conservation, government policy, energy prices, and macro-economic conditions.

The breakdown of oil demand by product was accomplished by examining the oil consumption patterns of specific end-use sectors. To project future oil consumption patterns in the transportation sector, for example, separate forecasts were developed for automotive, rail, marine, and air transport, and the fuels were projected accordingly, taking into account any efficiency improvements expected.

The product forecast from this analysis is shown in detail in Appendix B. Imported petroleum products were assumed to be held constant in the results of both of these demand forecasts at the 1973 level, as a result of governmental policy considerations. It is therefore possible to compare product imports with the domestic U.S. demand to arrive at the domestic refinery demand for the next decade. These refinery production expectations were used in the LP model studies.

c. Gasoline Grade Distribution -

For both of these demand forecasts, it is necessary to project the gasoline grade requirements over the next decade, under the scenarios pertaining to lead regulations. By consideration of the expected growth rate of introduction of new cars (requiring unleaded gasoline), new car imports, and automotive distribution by weight, the grade distribution under these scenarios was projected as defined in Table 6.

3. Key Product Specifications

The definition of future product specifications is quite important to the successful operation of the cluster and grassroots models. For example, in the study of sulfur regulations on unleaded gasoline, one of the common methods to lower the sulfur content is to hydrotreat the fluid catalytic cracker (FCC) feed stock. When this hydrotreating is accomplished, the sulfur level of all of the FCC products are diminished (not only the sulfur level of the FCC gasoline), including the sulfur level of blending components in the fuel oil pool. To actually represent the cost of sulfur reduction, therefore, a specification must be placed to prevent the fuel oil pool sulfur level from changing. Hence, in any study of the impact of a potential regulation on the refining industry, accurate definition of the product specifications for all of the major petroleum products must be considered in order that the computer model operate in a fashion which would be realistic in terms of petroleum industry flexibility or market demand.

The importance of economic factors in the determination of petroleum product specifications is well known. For example, there is usually a price premium associated with the lower sulfur levels of heavy fuel oil. In addition, there are performance requirements for certain product specifications, such as the distillation and volatility characteristics of motor gasoline. In recent years, however, the impact of governmental regulations on the specifications for petroleum products has become increasingly pronounced, such as a regulation which would specify the sulfur level of unleaded motor gasoline. Hence, an assessment is required of the likely future course of governmental regulations on major products over the next decade.

Table 6. GASOLINE GRADE REQUIREMENTS BY PERCENT

Grade Distribution %	1977					1980					1985					U.S. average		
PAD	I	II	III	IV	V	I	II	III	IV	V	I	II	III	IV	V	1977	1980	1985
A. No lead regulations																		
Premium (100 RON)	27	16	25	13	38	33	22	31	19	44	40	29	38	26	50	24	30	37
Regular (94 RON)	65	76	68	80	52	64	75	67	79	52	58	69	60	72	48	68	68	61
Unleaded (92 RON)	8	8	7	7	10	3	3	2	2	4	2	2	2	2	2	8	3	2
B. Unleaded with no lead phasedown																		
Percent of pool																		
Premium	15	5	13	3	22	4	1	3	1	5	0	0	0	0	0	12	3	0
Regular	54	63	56	66	42	37	39	38	40	31	0	0	0	0	0	56	37	0
Unleaded	31	32	31	31	36	59	60	59	59	64	100	100	100	100	100	32	60	100
C. Unleaded with lead phasedown[a]																		
Promulgated lead phasedown pool average, grams/gal.	1.0					0.5					b					1.0	0.5	b
Allowable grams of lead per gallon of leaded gasoline	1.74					1.66					b					1.74	1.66	b

[a] same distribution pattern used as in unleaded (Item B.)

[b] 100% unleaded gasoline

Complete identification of product specifications in the computer models is contained in Appendix C. The highlights of the analysis and the principal product specifications used are summarized here.

a. Motor Gasoline Specifications -

Among the most important product specifications for motor gasoline in such a study is the octane number of the several grades of motor gasoline to be produced from the refining industry. Survey data on the three grades of motor gasoline is shown in Table 7. In the modeling studies of the present investigation, the projected research and motor octane numbers for regular, premium and unleaded gasoline, respectively, over the remainder of the decade varied by region (Appendix C), but were approximately 93/85, 99/91, and 92/84. Some studies[10,11] may be interpreted to indicate that the unleaded gasoline octane numbers shown in Table 7 will be increased over the next decade. Evaluation of the impact of producing higher octane unleaded gasoline is included elsewhere[7].

In Table 8 are shown selected results of a survey on unleaded gasoline, broken down by district. It is apparent that the 92/84 specification on the research and motor octane numbers used in this study describes a large fraction of the United States marketing area, particularly since MON is the limiting specification. The average sensitivity is somewhat larger than used in the present study. This will make the study results conservative in principle; in practice, it will have no effect due to MON being the limiting specification.

The Reid vapor pressure of the gasoline pool, as shown in Table 7, varies significantly between summer operation and winter operation. Previous studies[12] have shown that the summer/winter operation can be effectively simulated by means of an average Reid vapor pressure, reflective of both summer and winter operations. Consequently, in the present program all gasoline specifications were set at 10.5 lbs. RVP.

It has also been reported[13] that realistic distillation specifications on motor gasoline must be used in computer simulations to ensure that the model adequately represents the refining industry. Table 7 provides historical data on distillation specifications for comparison with those

Table 7. MOTOR GASOLINE SURVEY DATA

	Grades of motor gasoline				
	Regular		Premium		Unleaded
	Winter 1974-1975	Summer 1974	Winter 1974-1975	Summer 1974	Winter 1974-1975
Research octane no.	93.4	93.4	98.9	98.9	92.3
Motor octane no.	86.1	85.9	91.6	91.5	84.0
Lead, g/gal	1.58	1.90	2.10	2.32	0.02
Reid vapor pressure, lb.	12.0	9.6	11.8	9.7	10.9
Distillation, °F					
20% evaporation	129	142	134	146	139
30% evaporation	152	164	161	172	166
50% evaporation	202	211	210	217	214

Source: U.S. Dept. of Interior, Bureau of Mines, Petroleum Products Survey Motor Gasolines, Summer 1974 and Energy Research & Development Administration, BER C/PPS–75/1 – Motor Gasolines, Winter 1974–75.

Table 8. MOTOR GASOLINE SURVEY, WINTER 1974-75
AVERAGE DATA FOR UNLEADED GASOLINE IN EACH DISTRICT

District name	Gr., ASTM D287 °API	Sulf., ASTM D1266 wt. %	Octane number			RVP, ASTM D323 lb
			RON ASTM D2699	MON ASTM D2700	$\frac{R+M}{2}$	
Northeast	59.2	0.029	92.8	83.9	88.4	11.0
Mid-Atlantic Coast	60.2	.027	92.5	83.8	88.2	11.4
Southeast	59.8	.024	92.5	83.7	88.1	11.0
Appalachian	60.6	.022	92.9	84.5	88.7	11.8
Michigan	61.7	.033	91.9	83.9	87.9	12.1
North Illinois	61.2	.026	92.3	84.3	88.3	12.2
Central Mississippi	62.5	.024	92.0	83.8	87.9	10.9
Lower Mississippi	61.2	.034	92.5	83.8	88.2	11.5
North Plains	63.3	.052	92.0	84.3	88.2	11.1
Central Plains	65.1	.037	92.0	84.3	88.2	10.8
South Plains	63.9	.033	92.0	84.6	88.3	10.8
South Texas	60.6	.019	92.0	83.7	87.9	11.1
South Mountain States	61.9	.038	91.5	83.4	87.5	9.7
North Mountain States	63.8	.033	91.5	83.6	87.6	10.0
Pacific Northwest	61.8	.010	92.7	84.7	88.7	11.0
North California	56.9	.016	93.2	83.9	88.6	9.4
South California	59.0	.044	92.5	83.5	88.0	9.7
Average	61.3	.029	92.3	84.0	88.2	10.9

Source: Energy Research & Development Administration, BER C/PPS–75/1 – Motor Gasoline, Winter 1974-1975.

placed on gasoline products as follows. For premium gasoline the 150°F distillation temperature is reached between 20 and 28% distilled overhead, and the 210°F distillation temperature is reached between 42 and 54% distilled overhead. With regular and unleaded grades the 150°F distillation point is reached between 20 and 30% distilled overhead, whereas the 210°F specifications were identical to those of the premium grade gasoline.

b. Sulfur Content of Residual Fuel Oils -

As indicated above, one of the key product specifications required to ensure that the model approximates realistic operation is the sulfur level of the residual fuel oil. This specification is important because the minimum cost approach of the LP model is to produce higher sulfur fuel oils rather than adding desulfurization and Claus plant investment. This subsection summarizes the methodology and results of our forecast for the U.S. fuel oil demand of differing sulfur contents. Of particular emphasis here is the sulfur level of residual fuel oils produced from domestic U.S. refineries, in contrast to the sulfur level of total U.S. residual fuel oil demand, which is influenced by imported fuel oils.

To determine the allowable sulfur content of fuel oil to be burned as refinery fuel (and not marketed) for each of the cluster models, an evaluation was made of the existing state regulations on allowable SO_x emissions. This analysis included an investigation of the regulations applicable to the particular refineries being simulated in the cluster models as well as those for the P.A.D. district the model was intended to simulate. From this analysis of regulations, sulfur specifications were determined for refinery fuel for each cluster model, ranging from 0.6% to 1.5% depending on the geographical location of the cluster model simulation. A complete discussion of the methodology and results of this analysis is presented in Appendix D.

The remainder of this section deals with the sulfur specification of residual fuel oils manufactured and marketed in the U.S. (as distinguished from fuel oils burned within the refinery or imported for domestic sales).

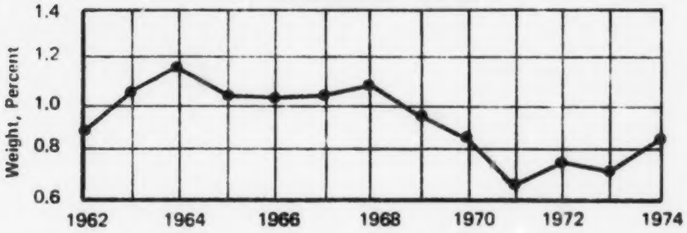
The forecast of the sulfur level of residual fuel oils manufactured and marketed in the U.S. was based upon an analysis of the current air quality regulations required by federal, state, and city agencies; the current status of these regulations, with particular attention to variances being granted; the likely future trend of environmental regulation; and the overall economic environment. In the course of this program, discussions have been held with federal, state, and city environmental protection authorities. A program of interviews with East Coast electric utility companies, accounting for over 90% of the total fuel oil consumed by East Coast utilities, was also conducted.

The current inflationary tendency in the United States and the U.S. policy of energy independence could be contributory factors to the relaxation of air pollution regulations, particularly if the use of domestic coal is to be emphasized. Tendencies to use higher sulfur fuel oils when meteorological conditions are favorable and lower sulfur oils when meteorological conditions are adverse will also play a potential role in the average sulfur level of the fuel oil burned in the U.S. during the next decade. On the other hand, environmental regulations now in effect will not be rapidly changed. Most of the existing variances are temporary and there will still be areas in the United States which are unlikely to grant or renew exemptions.

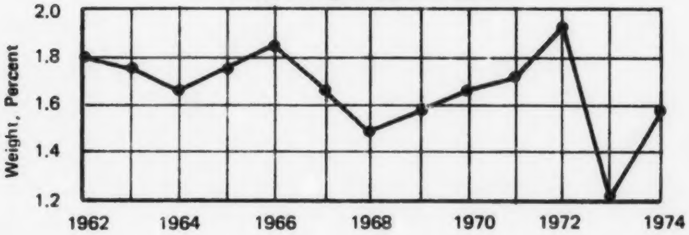
The historic trend of the sulfur content of heavy fuel oils manufactured and marketed in the United States is shown in Figure 3. It is apparent that the sulfur content of the lighter grade fuel oils has diminished considerably in the last five years. However, the trend of the heavier grade fuel oils is less evident. Table 9 shows the availability of residual fuel oil by sulfur level for the year 1973 and it is apparent that the refinery residual fuel oil production in each of the PAD districts has been at relatively high sulfur levels, between about 1 and 1.5% on average. However, considerable quantities of imported low sulfur oil is marketed, which allows the burning of fuel oils that will meet the statewide sulfur regulations discussed in Appendix D.

Our projections of future sulfur levels for U.S. fuel demand stem from the foregoing discussion and also draw upon more detailed information about likely developments in individual states. From a consideration of such factors it was projected that the sulfur content of the U.S. residual fuel oil demand would be between 1.1 and 1.4%.

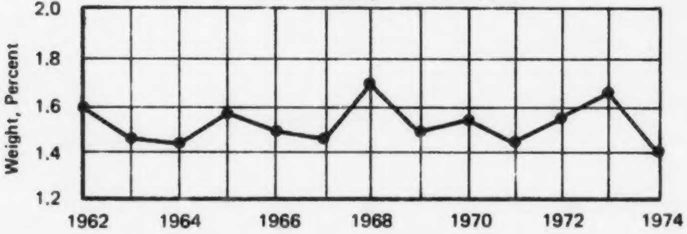
Grade 4 Burner Fuel Oils



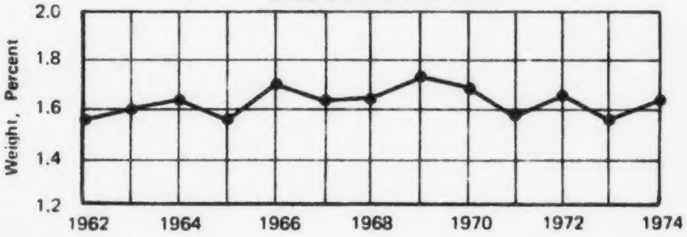
Grade 5 (Light) Burner Fuel Oils



Grade 5 (Heavy) Burner Fuel Oils



Grade 6 Burner Fuel Oils



Source: U.S. Dept. of Interior, Bureau of Mines, Petroleum Products Survey, Burner Fuel Oils, 1974

FIGURE 3 HISTORIC TREND OF HEAVY FUEL OIL SULFUR CONTENT AS PRODUCED AND MARKETED IN U.S.

Table 9. AVAILABILITY OF RESIDUAL FUEL OIL BY SULFUR LEVEL, 1973

(Thousands of Barrels)

P.A.D. District	Fuel oil source	Sulfur content, wt%				
		0-0.5	0.51-1.00	1.01-2.00	over 2.00	Total
I	Refinery production	11,743	15,834	16,112	8,569	52,258
	imports	232,889	130,258	74,732	160,814	598,912
II	Refinery production	985	30,368	25,952	13,815	71,120
	imports	1,654	1,964	1,719	770	6,107
III	Refinery production	12,790	26,462	9,927	39,276	88,455
	imports	201	2,303	547	1,408	4,459
IV	Refinery products	824	2,451	3,323	3,266	9,864
	Imports	0	0	0	0	0
V	Refinery production	70,348	7,385	47,528	7,639	132,900
	Imports	9,542	32	1,464	221	11,259
U.S. Total	Refinery production	96,690	82,500	102,842	72,565	354,597
	Imports	244,286	134,557	78,860	163,212	620,736

Source: U.S. Dept of Interior, Bureau of Mines, Availability of Heavy Fuel Oils by Sulfur Level, Dec, 1973.

For purposes of this study we assumed an overall U.S. average sulfur content for residual fuel of 1.3 wt.%, representing maximum sulfur levels of 1.4 wt.% east of the Rockies and 0.9 wt.% west of the Rockies. A parametric analysis assumed a U.S. average residual fuel sulfur content of 1.1 wt.%, the weighted average of 1.2 wt.% sulfur east of the Rockies and 0.75 wt.% west of the Rockies.

The importance of testing the sensitivity of study results to the overall U.S. average residual fuel sulfur level is highlighted in Table 10 for the East of Rockies grassroots, Scenario A. It can be seen that the impact on the industry simulation for variations between 1.4% (base case) and 1.2% (parametric run) sulfur level of the East of Rockies residual fuel oil pool is quite marked. As shown in that table, the imported residual fuel oil and the production from existing refineries must be added to the production from new East of Rockies grassroots refineries in 1985 to match the total residual fuel oil sulfur content on the East Coast. Because of the leverage effect of the small volume of residual fuel oil produced from grassroots refineries versus the volume available from imports and existing refineries, the variation in sulfur content of residual fuel oil produced in East of Rockies grassroots refineries is from about 0.6 wt.% to 1.8 wt.% depending upon whether the East of Rockies pool is at 1.2 wt.% or 1.4 wt.% (corresponding to overall U.S. pool averages of 1.1 wt.% and 1.3 wt.%, respectively). Obviously the cost of desulfurization capability in the grassroots refineries varies accordingly.

Other specifications on the residual fuel oil produced from the U.S. refinery industry in addition to the sulfur content were, of course, required. These specifications are summarized in Appendix C.

4. Processing and Blending Routes

The computer simulation of the U.S. refining industry utilized cluster models, chosen to represent the existing refinery structure, and grassroots models, chosen to represent either new grassroots refinery construction or major expansions of existing refineries. The cluster models were allowed to add new downstream process equipment of reasonable economic size. Accordingly, these models had essentially the same processing and blending capability during the study period.

Table 10. GRASSROOTS REFINERY FUEL OIL SULFUR PROJECTION – 1985
SCENARIO A – EAST OF ROCKIES ONLY

Total East-of-Rockies[a]		Imports		Existing refineries[b]		Grassroots refineries[b]	
Sulfur content (wt%)	Fuel oil (MBPD)	Sulfur content (wt%)	Fuel oil (MBPD)	Sulfur content (wt%)	Fuel oil (MB/CD)	Sulfur content (wt%)	Fuel oil (MBPD)
1.2	2,852	1.28	1,797.7	1.44	561.3	0.63	493
1.4	2,852	1.28	1,797.7	1.44	561.3	1.78	493

[a] Fuel oil produced in refineries plus imports

[b] Fuel oil produced and marketed in U.S.

The unit yields and product properties were obtained from a variety of sources, including the petroleum literature and process licensors. The ability of the cluster models to represent actual refineries when using these unit yields and product properties was confirmed in calibration studies, discussed below. These same unit yields and product properties were also used in the grassroots refinery simulations. A complete discussion of the unit yields and product properties available in the computer program is contained in Appendix H.

Hydrogen generation in the cluster models was obtained solely from refinery gas or imported natural gas. In the grassroots refinery, the first option was also allowed, as well as the ability to generate hydrogen from petroleum naphtha.

Coking capacity for the cluster refineries was maintained at a level similar to that derived during the calibration runs. No coker capacity was allowed to be constructed in the East Coast grassroots refinery, because of market demand considerations. Coker capacity in the West Coast grassroots refineries for the several scenarios discussed above was not allowed to exceed that available from Scenario C. There was a tendency for coker capacity to be greatly increased as an inexpensive means to remove sulfur for Scenarios D, E, and F, resulting in coke production exceeding likely West Coast demand capabilities. Visbreaking and solvent deasphalting were not allowed in the grassroots models.

In the cluster refineries desulfurization of atmospheric bottoms and vacuum bottoms was not allowed, because the cluster refineries were intended to be descriptive of the current operation of certain existing refineries. In the grassroots refineries, both atmospheric and vacuum bottoms desulfurization were allowed.

As discussed above, the properties of the products from the fluid catalytic cracking (FCC) unit are particularly significant to the assessment of the impact of the possible EPA regulation. For reasons already described, the sulfur distribution of the products from this processing unit is not well defined at present. Moreover, FCC gasoline is a major source of sulfur to the unleaded gasoline pool and the combustion of coke in the regenerator is a major source of gaseous sulfur oxide emissions in the refinery. Consequently the sulfur distribution among several products of the FCC unit were studied in a parametric run. The distribution shown in Table 11 for the Large Midwest cluster illustrates the cases considered. Additional detail on the product properties for the FCC unit as well as the many other units used in the models are discussed in Appendix H.

Another unit critical to the success of a study of motor gasoline properties is the catalytic reforming unit. A significant amount of effort was expended in the development and confirmation of the yields and properties of this particular unit. Yields for low pressure operation, high pressure operation, and an average operation of reformers across the industry were simulated in detail for several different cases to ensure that the assumptions made in the yield patterns of this critical unit did not significantly detract from the assessment of the impact of the possible regulation under consideration. A detailed discussion of the reformer evaluations is contained in Appendix H.

Another factor critical to the success of the impact study is the blending octane numbers of reformate, FCC gasoline, etc., for the variety of feedstocks, operating conditions, and gasoline pool compositions used in the study. Because of their importance, blending numbers used in this study were circulated to representatives of the API/NPRA Task Force assisting in the study. For the purposes of the study of the sulfur level of unleaded gasoline, there was good agreement between the blending numbers utilized in the present study and the suggestions made by members of this task force, as summarized in Table 12.

In the model, two distinct hydrogen systems were employed. A high purity hydrogen system was fed by steam-methane reforming and was delivered to high pressure desulfurization and hydrocracking units. The low purity hydrogen system was produced from catalytic reformer units and was distributed to low pressure desulfurization units. Allowances were provided for interchanges from the high purity hydrogen system to the low purity hydrogen system. In addition normal allowances for solution losses and flaring circumstances were also provided. Careful analysis of this hydrogen distribution system indicates that it is a reasonable simulation of refinery systems and will be an adequate description for the purposes of the study. If additional purification of the low purity hydrogen system

Table 11. FCC UNIT SULFUR DISTRIBUTION LARGE MIDWEST CLUSTER, 65% CONVERSION

Stream	Percentage distribution of feed stock sulfur	
	Base, 1985	Parametric run
H_2S	39.7	40.0
Gasoline	4.3	6.0
Gas oil	27.7	33.0
Clarified oil	22.5	15.0
Coke	5.9	6.0

Table 12. ILLUSTRATIVE BLENDING OCTANE NUMBER COMPARISON
(Clear Motor Octane Number)

Stream	ADL model	Ethyl	DuPont	Marathon	Citgo
90 Sev. reformate	80.1	81-82	82	–	–
100 Sev. reformate	86.0	87-88	87	–	87.1
FCC gasoline (full range)	80.0	80	79-80	82-83	79.9
Alkylate	89.8	–	–	92-93	88.7

is required cryogenic units can be added without having a major impact on the overall capital investment penalty associated with the potential regulations.

5. Calibration of Cluster Models

The U.S. refining industry is composed of nearly 300 individual refineries scattered throughout the country, each characterized by a unique capacity, processing configuration, and product distribution. There are, however, logical regional groupings of major refineries with similar crude supply patterns, processing configurations, and product outputs. Therefore, the cluster model approach was developed for this study, in which the existing U.S. refining industry was simulated by the average operation of three similar refineries located in each of six selected regions. The selection of the three refineries as well as the six selected regions was accomplished with the assistance of the API/NPRA Task Force cooperating in this study. The most important criteria guiding the selection of these cluster models were: (1) each cluster model was to represent, as closely as possible, a realistic mode of operation, in that processing units were to be of normal commercial size and that plants would be allowed normal flexibility in regard to raw material selection and product mix, (2) the cluster model crude slate, processing configurations, and product outputs were to bracket as best as possible those variations peculiar to each geographic region.

The final selection of refineries to be represented by the cluster models is shown in Table 13.

PAD District I was simulated by three refineries in the Philadelphia-New Jersey area with capacities ranging from 160,000 to 255,000 bbls/day. PAD District II was characterized by two refinery clusters, one represented by the Large Midwest cluster model simulating the Indiana/Illinois/Kentucky district and processing high sulfur crudes. The Small Midcontinent cluster was also used to represent PAD II, simulating refineries in the Oklahoma/Kansas/Missouri district. This Small Midcontinent model was also used to represent small refiners in PAD District II, as described in Appendix G. PAD District III, which represents about 40% of the U.S. refining capacity, was simulated by two models because of its overall importance and because

Table 13. REFINERIES SIMULATED BY CLUSTER MODELS

PAD district	Cluster identification	Refineries simulated	1973 Crude capacity, MB/CD
I	East Coast	Arco – Philadelphia, Pa.	160.0
		Sun Oil – Marcus Hook Pa.	163.0
		Exxon – Linden, New Jersey	255.0
II	Large Midwest	Mobil – Joliet, Illinois	160.0
		Union – Lemont, Illinois	140.0
		Arco – East Chicago, Illinois	135.0
II	Small Midcontinent	Skelly – El Dorado, Kansas	67.0
		Gulf Oil – Toledo, Ohio	48.8
		Champlin – Enid, Oklahoma	48.0
III	Texas Gulf	Exxon – Baytown, Texas	350.0
		Gulf Oil – Port Arthur, Texas	312.1
		Mobil – Beaumont, Texas	335.0
III	Louisiana Gulf	Gulf Oil – Alliance, La.	174.0
		Shell Oil – Norco, La.	240.0
		Cities Service – Lake Charles, La.	240.0
V	West Coast	Mobil – Torrance, California	123.5
		Arco – Carson, California	165.0
		Socal – El Segundo, California	220.0

differing types of refinery configurations could be identified. The Texas Gulf cluster was typified by a crude capacity exceeding 300,000 bbls/day and heavy involvement in petrochemicals, lubes and other specialty products. The Louisiana Gulf Coast cluster represented refineries between 174,000 and 240,000 bbls/day and processed a single source of sweet crude. PAD District V was simulated by a West Coast cluster model and was represented by refineries in the Southern California area. PAD District IV was not explicity simulated because it represents less than 5% of the total U.S. refining capacity. It was included in the scale up, however, as discussed in Appendix G.

Additional detail on the development of the cluster model concept is contained in Appendix F.

Upon completion of the development of the cluster refinery modeling concept, an extensive calibration effort was undertaken by ADL with the assistance of the Bureau of Mines, Environmental Protection Agency, and the API/NPRA Task Force. A complete discussion of the calibration effort is contained in Appendix I. Only the highlights of this effort will be summarized here.

The annual refining surveys published in the Oil and Gas Journal were used as the basic reference source for determing the cluster model processing configurations, allowing simulation of those refineries listed in Table 13. This source also provided the processing unit capacity available in these cluster refineries, used to limit the available capacity in the cluster models.

The 1973 annual input and output data was furnished by the Bureau of Mines for the aggregate of the three specific refineries comprising each individual cluster model (Table 13). These data included the following: (1) crude oil and other raw materials fed to the refineries, broken down by individual state of origin for domestic crudes and by country of origin for foreign sources; (2) statistics on fuel consumed for all purposes in the refineries; and (3) all petroleum products manufactured by refineries for the year.

Each individual oil company furnished EPA the following proprietary data for 1973: (1) gasoline grade distribution and the associated octane levels and lead levels for each grade, (2) total gasoline volumes and average sulfur contents, (3) crude slates and sulfur levels, and (4) intakes and operating conditions on selected units. The EPA averaged these data to obtain information representing the cluster models, and supplied these data to ADL.

As summarized in Appendix I, four main areas were considered to compare the degree of calibration to the cluster models. These were: (1) overall refinery material balance (i.e., volume of the crude intake required to balance specified product demands and internal fuel requirements), (2) refinery energy consumption, (3) processing configuration, throughputs and operating severities, and (4) key product properties (e.g., gasoline clear pool octanes, lead levels, etc.).

A selected result showing a portion of the calibration results for the Large Midwest cluster is presented in Table 14. Shown here is the crude intake, as specified by the Bureau of Mines data and industry data to provide a given product outturn, as well as a result of the computer model simulation. Also shown is the energy consumption required for this crude intake and product outturn, and a summary of the principle refinery process operations. It is apparent that the agreement of the model prediction and the data base for this Large Midwest cluster is excellent. Additional detail on other clusters as well as other calibration criteria are contained in the discussions of Appendix I.

6. Existing and Grassroots Refineries

The existing U.S. refining industry was simulated by means of the six cluster models, as discussed above. New grassroots capacity was required when atmospheric distillation requirements exceeded 90% of the calendar day capacity listed in the Oil and Gas Journal for the specific refineries being simulated by these cluster models. In practice, operation at 100% of the calendar day capacity cannot be achieved due to unscheduled refinery turnarounds, limitations on secondary processing capacity imposed by product specifications, variations in crude slate, crude supply restrictions, regional and logistical constraints, and imbalances between individual product output and market demand. The industry has historically achieved about 90% of calendar day capacity[14], so this limitation was used to provide a conservative assessment of the penalties associated with the

Table 14. CALIBRATION RESULTS FOR LARGE MIDWEST CLUSTER

		BOM Data	Industry data	Model run
Material balances				
Total crude intake MB/CD		146.1	145.5	145.5
Energy consumption				
Purchased natural gas MB/CD (F.O.E.)		.2	–	.2
Total fuel consumption MB/CD (F.O.E.)[a]		8.1	–	8.4
Electricity MKWH/D		843	–	545
		Oil and gas capacity MB/SD	**Industry data**	**Model run**
Processing summary				
Catalytic reforming	Intake MB/CD	32.7	27.8	27.6
	severity RON	–	90.7	90.0
Catalytic cracking	Intake MB/CD	55.0	51.2	48.7
	conversion % vol.	–	74.9	74.3
Alkylation	Production MB/CD	13.4	11.4	12.0
Coking	Intake MB/CD	15.8	13.6	14.1

[a] Excludes catalyst coke

potential regulation. However, since all penalties are reported as differences between the various scenarios considered, a precise figure of calendar day utilization is unnecessary.

To meet increased product demand and provide additional crude required to manufacture low sulfur gasoline, an increase in crude run to each cluster is required as the decade proceeds. The existing refining industry (cluster model) is allowed to expand down-stream processing capacity as required to meet these constraints. However, when the crude run reaches the limitation of the atmospheric distillation capacity, the expansion of the cluster model is no longer allowed, and new grassroots facilities must be constructed.

The grassroots models used in this study represent either new, basic grassroots refineries to be built in the United States over the next decade or major expansions in crude distillation capacity in existing refineries.

Those major expansions of existing refining capacity which have taken place within the last few years are often noted by new atmospheric distillation capacity, new tankage requirements, and frequently new or greatly expanded production of refinery products which have otherwise been only a minor component of total product outturn. An example of such major new expansion is the production of large quantities of low sulfur fuel oil. In any event, this type of new major refinery expansion frequently exhibits relatively little interaction with existing refinery processing units, and little additional flexibility for product blending over that of a refinery built on a segregated grassroots basis. Therefore, any requirements for distillation capacity in the industry were simulated by addition of new grassroots capacity. The product outturn and therefore the crude run required for this new grassroots capacity was chosen to be sufficient to balance the product demand and product quality requirements for the United States as a whole. New grassroots construction was simplified by consideration only of a location typified as "east of the Rockies" and another location typified as "west of the Rockies", each location with its own crude slate as discussed in Appendix A.

The yields and product qualities for new capacity additions were identical to those provided in the cluster model operation, with the exception of catalytic reforming, wherein all new capacity was assmumed to utilize a yield structure and investment representative of low pressure, bimetallic reformers.

The refinery fuel system for both the cluster models and the grassroots models was constrained to meet environmental regulations typical of the refining regions in which these models operated. A complete discussion of the allowable refinery fuel sulfur level and the methodology by which it was determined is contained in Appendix D.

7. Economic Basis for Study

The estimation of capital investments and operating costs for petroleum processing units is difficult at the present time because of the rapid rate of inflation and the long elapsed time that it takes to build a large and complex petroleum refinery. Investment estimates were obtained by using data from a variety of literature sources, such as the Oil and Gas Journal, and by extensive discussions with process licensors and contractors. In order to minimize the effect of future cost escalations on the cost estimations, the investment estimates were made on a 1975 first quarter basis. This investment estimate will be applicable for refineries which were conceived, designed, equipment ordered, and constructed all within the first quarter of 1975. Escalation of these costs are reported separately in order to allow recalculation of these ultimate investments on other inflation schedules if so desired.

Onsite capital investments were estimated by compositing the information available from these several sources. The onsite process unit estimates used in this study are typified in Table 15. Additional detail of the specific information on capital investments is contained in Appendix H.

The primary purpose of the economic study was to determine the capital investment and operating costs associated with the production of low sulfur gasoline. Consequently economic penalties for the cluster models were determined by comparing Scenario D versus Scenario C, for example for 100 ppm gasoline. Therefore, only the incremental downstream capacity required for Scenario D versus Scenario C was determined and costed. As part of the analysis, charges were assessed for the utilization of spare, idle capacity which was available in 1974 but was incrementally consumed at a

Table 15. ONSITE PROCESS UNIT COSTS

Process unit	Size basis, MB/SD	Investment, \$/B/SD 1975, 1st quarter
Atmospheric distillation	100	165
Vacuum distillation	40	185
Catalytic cracking	40	925
Catalytic reforming (low pressure)	20	800
Alkylation (product basis)	10	1,400
Isomerization – once through	10	620
Isomerization – recycle	10	1,240
Hydrocracking (high severity)	25	1,400
Naphtha hydrotreating	20	235
FCC/coker gasoline hydrotreating	15	320
Light distillate hydrotreating	30	230
Heavy distillate hydrotreating	30	250
Vacuum gas oil desulfurization (also FCC feed)	25	370
Atmospheric residual desulfurization	50	775
Vacuum residual desulfurization	15	1,500
Coking – delayed	10	930
Hydrogen generation – Methane \$/MMSCF/SD	50	230[a]
– Naphtha \$/MMSCF/SD	50	260[a]
Sulfur recovery (95% removal) – \$/short tons/SD	100	25,000
Sulfur recovery (99.95% removal) – \$/short tons/SD	100	50,000

[a] \$/MSCF/SD

Table 17. GRASS ROOTS REFINERY CAPITAL INVESTMENT

Location:	**East of Rockies**	**Scenario: C**
Crude processed:	**Arabian Light**	
Refinery complexity:	**7.01**	

Process unit	Throughput (MB/SD)	Onsite investment (millions of dollars)
Atmospheric distillation	231.7	28.1
Vacuum distillation	100.1	12.5
Catalytic reforming	52.2	36.5
Catalytic cracking	47.4	42.0
Hydrocracking	26.6	32.2
Isomerization-recycle	11.5	13.8
Alkylation (product basis)	14.9	17.8
Hydrogen manufacture (MMSCF/SD)	62.1	13.3
Desulfurization		
Full range naphtha	62.9	9.4
Straight run distillate	26.4	6.7
Vacuum residue	21.1	27.0
Sulfur recovery and amine treat (short tons/SD)	366	9.4
Total onsite investment		248.7
Offsite and associated costs at 151.0% onsite investment		375.6
Working capital at 70.0% onsite investment		174.1
Total cost		798.4
Investment/B/SD		3,446

Operating costs were determined by a direct assessment, on a unit-by-unit basis, of either the additional downstream processing requirements of the cluster models or the complete refinery requirements for the grassroots models. Catalysts and chemicals, cooling water and electricity were determined from the processing unit intakes themselves and tetraethyl lead was determined as required to meet the gasoline blend requirements. Maintenance and manpower assessments were determined on an off-line basis, i.e., they were not determined by the computer model directly. Manpower requirements were determined both for severity upgrading and for new unit construction by examination of operating requirements of the particular units under consideration. Maintenance costs were assessed at a level of 3% of onsite investments and 1.5% of offsite investments.

In addition a capital charge was assessed for new investment in any processing unit, either in a cluster model or a grassroots model. The capital charge was taken to be 25% of the total capital investment, which is approximately 12% rate of return, on an after tax, discounted cash flow basis. The same capital charge was applied to both the downstream capacity additions in the cluster model and new grassroots facilities in a grassroots model, on the philosophy that the amortization for both types of investments must be approximately equivalent in the present economic climate. A typical level of cash operating expenses (exclusive of capital charge) for the grassroots refinery was approximately 80¢ per barrel of crude capacity.

An assessment of cost escalations over the next decade was made to reflect the actual capital investment which may be required in the time interval in which the actual refinery construction will take place. Such an escalation of costs can result from increases in the costs of refinery equipment which outpace the general inflationary trend in the United States. As a basis for this cost escalation, an approach similar to the usual construction S-curve escalation analysis was conducted, in which the annual escalation for the years 1975-1985 were taken to be 20%, 17%, 15%, 10%, 10%, 10%, 9%, 9%, 8%, 8%, 8%. Clearly, assessments of the rate of cost escalation for the coming decade are highly intuitive and will depend upon a varieity of factors, such as further increases in foreign oil prices, general inflationary tendencies in the United States, and many others which are difficult to predict with any degree of precision. Indeed, cost escalation now appears to be flat through 1975. Therefore, the impact of the potential regulation on the refinery industry will be summarized in the following body of the report both on 1975 first quarter basis and on an escalated basis, with the above assumed escalation schedule.

8. Scale Up to National Capacity

In the cluster model approach, the U.S. refining industry has been simulated by six individual cluster models, each cluster representing three existing refineries in different regions of the United States. To represent the impact on the U.S. refining industry, it is necessary to scale up the results of the cluster model analysis to a regional and a national basis. From this estimate of the total production capability of the existing U.S. refining industry, requirements of the new grassroots models are obtained by subtracting existing capability from the total product demand of the U.S. refining industry. Appendix G discusses the scale up method and the derivation of product demands for grassroots refineries in detail.

The general method employed in scaling up data from the cluster runs to the existing U.S. refining industry is to compare the gasoline outturn of the region being simulated by the cluster model to that of the cluster model itself. For example, the East Coast cluster represents the refineries in PAD District I, so a scale up factor in 1973 of 7.127 is used, since this is the ratio of gasoline production of District I to the gasoline production of the East Coast cluster. However, the cluster model used for PAD I is known to be typical only of the major gasoline producing refineries in that region. Therefore, there is, by definition, a quantity of atypical refining capacity which is not represented by the yields used in the East Coast cluster model. Hence an estimate was made also of the atypical refining capacity in PAD I, to be included as a component of the scale up of the East Coast cluster model results to PAD I.

PAD II is represented by two cluster models. It has been assumed in scale up that the Small Midcontinent cluster represents operations of the Oklahoma/Kansas/Missouri district and that the balance of District II is represented by the Large Midwest cluster. Similarly, in PAD III, it has been assumed that the Louisiana Gulf cluster represents the Louisiana

Gulf refining district and the Texas Gulf cluster represents the balance of PAD III.

The West Coast cluster is assumed to represent the operation of PAD V. PAD IV was not represented by a specific cluster model so that the total refining capacity of PAD IV was similarly included as an atypical factor in the scale up analysis.

The results of the application of this scale up method, when composited for the total U.S. refining industry are shown in Table 18, for 1973. Here, the crude consumption by the cluster models agrees with the Bureau of Mines data to within about 2% and the total refinery intake agrees to within about 1%.

The major refinery products agree with the Bureau of Mines data within about 5%, with the exception of LPG (which was a swing product in the computer runs) which deviates from the Bureau of Mines data by about 15%. The total product outturn agrees with the Bureau of Mines data to within about 2%. Therefore, it is felt that the model scale up method is calibrated well with the Bureau of Mines data for the purposes of the present study, which emphasizes total energy penalties of the refinery and addresses itself to gasoline production capability. For other types of studies, the scale up method could be further refined, if so desired, to provide a closer match of the other minor products from the refining industry.

Model results for the study years of 1977, 1980, and 1985 were scaled up using the atypical refining concept described above. In 1977 scale up factors were based on meeting gasoline demand for the total U.S. For 1980 and 1985, however, the scale up factor approach was based on total crude run in each cluster and the effective crude oil distillation capacity for the region being simulated by that cluster. The scale up factors used were calculated by making the crude run in each region equal to the effective crude oil distillation capacity for that region, defined as 90% of the calendar day rated capacity.

Table 18. MODEL SCALE-UP COMPARISON, 1973

U.S. total input/output data, thousands of barrels

Refinery intakes/outturns	Cluster model results	Bureau of Mines data	Deviation of model from B.O.M. data (%)
Intakes:			
Crude oil	12,713.6	12,430.7	2.3
Butanes	254.2	219.8	15.6
Natural gasoline	365.2	439.2	16.8
Other	167.6	281.3	–
Total intake	13,500.6	13,371.0	1.0
Outturns:			
LPG	401.2	349.8	14.7
Gasoline	6,572.1	6,572.2	0
Naphtha	227.5	234.7	3.1
BTX	164.5	156.7	5.0
Distillate fuel oil	3,157.9	2,992.8	5.5
Residual fuel oil	956.0	971.5	1.6
Other	1,886.7	1,849.7	–
Total outturn	13,365.9	13,127.4	1.8

As discussed in Appendix B, the import levels of products were held constant at the 1973 level for the coming decade. Therefore, after scaling up of the cluster results, adding atypical factors, and adding import levels, the product outturn from the grassroots refineries could be obtained by difference from the forecast total petroleum products demand. The results showed that by 1980 seven new grassroots refineries at approximately 200,000 BPD each would be required in PAD Districts I through IV and two new refineries would be required to meet PAD District V product demands. By 1985, a total of fifteen new refineries were required for PAD District I through IV and a total of three refineries were needed for PAD V.

The utilization of such scale up factors allowed a direct assessment of the total energy penalties associated with each of the scenarios under discussion, as well as an assessment of the operating costs required to meet the possible regulation. However, capital investments were not determined solely by a direct utilization of the scale up approach, because this approach does not weight sufficiently heavily the capital requirements of the small refineries simulated by the Small Midcontinent cluster. Therefore, an additional factor was utilized in a scale up for capital costs, as discussed in detail in Appendix G. Such an approach adequately includes the dollar cost to the small refiner as a component of the overall cost to the industry, because his percentage of the total cost is relatively small. However, it does not adequately address the total impact on the small refiner nor the possible impact on the competitive structure of the petroleum industry.

III. STUDY RESULTS

A. BACKGROUND DISCUSSION

In the manufacture of gasoline, blending of different components is required which, when mixed together, produce a product meeting the required specifications. Certain blending components have sulfur levels much higher than others and it is particularly these components whose sulfur levels must be reduced in order to supply a blended low sulfur gasoline.

The two components normally found to have the highest sulfur levels are those gasolines produced from the fluid catalytic cracking (FCC) process and from the coking process. The sulfur level of these gasoline components is primarily dependent on the sulfur level of the feed stream to these processes. However, the relationship between the gasoline sulfur level and the feed sulfur level is not always the same for feed streams from different crude oil sources. Limited data is available on this relationship, which is critical in a study of the impact of manufacturing low sulfur gasoline. A recent study conducted by Gulf Research[15] on the feed sulfur distribution to the products in catalytic cracking units highlighted the differences between feed types. The percentage of feed sulfur found in the gasoline varied from a low of 3.5% to a high of 9.5%. The assumptions with regard to sulfur distribution in FCC products used in this study have been based on the work done by Gulf Research.

There is less information on the sulfur distribution in coking units. However, the amount of coker gasoline in the gasoline blend is much lower than FCC gasoline. Also, coker gasoline has been assumed to be split into a light stream, which goes directly to gasoline blending, and a heavy stream, which is fed to the catalytic reforming process and is therefore desulfurized in the reformer feed hydrotreater. Hence, the impact of coker gasoline on the sulfur level of the gasoline blend is much less than that of FCC gasoline, even though its inherent sulfur content is higher than that of FCC gasoline in any given cluster model.

The sulfur content of straight run naphtha can also be high, but the value is well known. Such naphthas are normally desulfurized before blending in a low sulfur pool.

The sulfur level of FCC gasoline can be reduced by either desulfurizing the feed to the catalytic cracking unit or by direct desulfurization of the FCC gasoline. The first method is usually preferable if it can reduce the sulfur levels sufficiently to meet the required level in gasoline, because of the associated yield benefits of FCC feed hydrotreating. By contrast, direct desulfurization of the FCC gasoline has associated disadvantages. Desulfurization of whole FCC gasoline results in a significant reduction of its clear octane numbers because high octane olefinic compounds are saturated in the presence of hydrogen into low octane parraffinic compounds. As a result, it is necessary to split the desulfurized catalytic cracker gasoline into a light fraction, which is routed direct to gasoline blending, and a heavy fraction, which must be reformed to improve its octane to an acceptable level. It is important to note, however, that direct desulfurization of FCC gasoline can achieve much lower gasoline sulfur levels than FCC feed hydrotreating.

One variation in the method of direct desulfurization of catalytic cracker gasoline is to split the FCC gasoline into a light fraction and a heavy fraction prior to desulfurization. Evidence to date suggests that approximately 85% of the sulfur in FCC gasoline is contained in the heaviest 25% of the gasoline. By desulfurizing only the heavy fraction, a major proportion of the sulfur is removed and the reduction of octane is much less since the olefinic compounds are contained in the light fraction. The option was not allowed in the base runs because of a lack of quantitative information on the processing steps employed.

Only direct desulfurization of a light coker gasoline has been considered as a method of reducing its sulfur content (the heavy coker naphtha is reformed). Direct desulfurization of light coker gasoline has only been considered in conjunction with the direct desulfurization of FCC gasoline. In practice, the same desulfurization unit could be used for both light coker gasoline and FCC gasoline. Desulfurization of light coker gasoline alone was not allowed because of the uneconomic size of the unit that would be required.

One other alternative to reduce the impact of high sulfur light coker gasoline on the gasoline pool is to burn small quantities as refinery fuel.

In blending of gasolines to 100 ppm and 50 ppm, the computer does not provide any tolerance in the blending of gasoline component sulfur levels, i.e., the gasoline blends are exactly at 100 ppm or 50 ppm. The results of this study are therefore considered to reflect what will be required to produce unleaded gasolines which on average meet sulfur levels of 100 ppm and 50 ppm. Should any proposed legislation set maximum specifications of 100 ppm and 50 ppm, it would be necessary to set lower target levels for refiners, probably at 80 ppm and 40 ppm. This blending tolerance would be required to ensure that the customer never received gasolines exceeding 100 ppm and 50 ppm. The implications of setting maximum specifications are discussed later.

The detailed results showing unit throughputs, severities, gasoline blends, inputs and outputs are given in Appendix J for the base case (Scenario C), for the manufacture of 100 ppm unleaded gasoline (Scenario D) and for the manufacture of 50 ppm unleaded gasoline (Scenario E). A discussion of those results now follows.

B. MANUFACTURE OF 100 PPM GASOLINE

1. 1985 Results

With the exception of the Large Midwest cluster, 100 ppm unleaded gasoline was manufactured in all the cluster and grassroots model runs by desulfurization of FCC feedstock, thereby reducing the sulfur level of the FCC gasoline. In the Large Midwest cluster this method was not capable of lowering the sulfur level to 100 ppm and direct desulfurization of FCC gasoline and some light coker gasoline was required.

As summarized in Table 19, the crude oils processed in the Large Midwest cluster have an average sulfur level of 1.4 wt. %, the highest of all the cluster models. This factor, along with the high level of FCC gasoline

Table 19. RELATIONSHIP OF CRUDE SULFUR LEVEL, FCC INTAKE AND METHOD CHOSEN TO MANUFACTURE LOW SULFUR (100 PPM) UNLEADED GASOLINE-1985

	Cluster					
	East Coast	Large Midwest	Small Midcontinent	Louisiana Gulf	Texas Gulf	West Coast
Crude sulfur level, wt %	1.08	1.4	0.53	0.33	0.76	1.14
FCC intake, % of crude run	30	35	34	37	27	25
Coker intake, % of crude run	–	10	6	8	5	20
Desulfurization option chosen	FCC feed	FCC gasoline	FCC feed	FCC feed	FCC feed	FCC feed

and coker gasoline in the gasoline pool, makes the FCC feed desulfurization route for the Large Midwest cluster incapable of producing 100 ppm gasoline. Catalytic cracking throughput is over 35% of crude run and coking throughput is 10% of crude run. This cluster model does not have any hydrocracking which, in all other clusters, provides a significant volume of gasoline which is virtually sulfur free. Because direct desulfurization of FCC gasoline is required, there is a significant increase in the requirement for catalytic reforming as well, due to the loss of octane in the FCC gasoline as a result of desulfurization.

The load on the Claus plant is a complex function of crude run, sulfur content of the crude, amount of desulfurization capacity, and whether FCC feed or FCC gasoline is being desulfurized. Furthermore, the amount of each of these generally varies over the study period. Nevertheless, as shown in Appendix J, the quantity of sulfur produced generally increases for the 100 ppm gasoline case (Scenario D) relative to the base case (Scenario C), particularly after consideration of round-off error.

The West Coast cluster has the next highest average crude oil sulfur level, 1.14 wt. %. However, catalytic cracking throughput is much lower than in the Large Midwest cluster, at about 25% of crude run. The West Coast cluster has the highest level of coking, with coker throughputs at 20% of crude run. Light coker gasoline produced in the coking operation is of a relatively low octane but has an extremely high sulfur level. To avoid the need to desulfurize FCC gasoline, approximately 1.5 MB/CD of light coker gasoline was allowed into the refinery fuel system. Taking into account the resulting heat equivalency losses (and in practice some possible investment in conversion of burners), that was still a much more attractive route than forcing all the light coker gasoline into the gasoline pool and having to desulfurize FCC gasoline.

The East Coast cluster, with an average crude oil sulfur level of 1.08 wt. %, has an FCC throughput of 30% of crude run, but does not have a coking unit. It is able to meet the 100 ppm specification with FCC feed desulfurization.

The Texas Gulf cluster has catalytic cracking requirements at 27% of crude run and coking at 5% of crude run. However, the average sulfur level of the crude oil processed is 0.76 wt. % and FCC gasoline desulfurization was avoided. Only FCC feed desulfurization was used to manufacture 100 ppm gasoline.

The Small Midcontinent and Louisiana Gulf clusters, with average crude oil sulfur levels of 0.53 wt. % and 0.33 wt. %, respectively, are able to meet the 100 ppm level with FCC feed desulfurization.

In the grassroots models, the 100 ppm level was also achieved with FCC feed desulfurization. Additional refining capacity East of the Rockies was simulated with both a sour crude oil (Arabian Light) and a sweet crude oil (Nigerian/Algerian mix) refinery. The sour crude oil refinery, although having a crude oil sulfur level as high as 1.7 wt. %, needed a catalytic cracking throughput of only 23% of crude runs and was thus able to avoid FCC gasoline desulfurization. No coking was allowed in the East of the Rockies grassroots, because of marketing considerations.

Additional refining capacity West of the Rockies was assumed to run 100% Alaskan North Slope crude oil, with a sulfur level of 0.96 wt. %. However, the catalytic cracking requirement was only 16% of crude run, so that gasoline at a 100 ppm sulfur level was achieved with FCC feed desulfurization.

2. 1980 Results

Before executing the 1980 model runs, certain restrictions were placed on the processing choices available within the model. These restrictions were based on the results of the 1985 runs and were used to avoid the selection of different processing options to produce low sulfur unleaded gasoline in 1980 compared with 1985. Processing options not chosen in the 1985 results were not made available in the 1980 runs. For example, the Large Midwest cluster required FCC gasoline desulfurization to meet 100 ppm sulfur gasoline in 1985. Therefore, in 1980 the alternative of FCC feed desulfurization was not allowed in this cluster model.

In 1980 the percentage of total gasoline produced as low sulfur, unleaded gasoline is only 60%; hence, some of the cluster models are able to meet 100 ppm sulfur gasoline without desulfurization facilities. This is achieved by blending the high sulfur gasoline components into the leaded gasolines and the low sulfur components into the unleaded gasoline. There is, however, a loss of gasoline production (which is made up by grassroots refineries) because of the non-optimum blending of gasoline from an octane standpoint.

The Texas Gulf, Louisiana Gulf, Small Midcontinent and West Coast cluster models did not require desulfurization facilities by 1980. They do require some increases in severity and throughput of gasoline-producing units to compensate for octane losses as a result of different blending schemes. They produce reduced gasoline volumes when compared with the unrestricted gasoline sulfur level case. This deficit of gasoline is met by the grassroots models which do, of course, require desulfurization facilities. It would therefore be misleading to conclude that no desulfurization facilities will be required in practice by 1980 for the regions represented by these four clusters. Desulfurization facilities will be required by 1980 in all regions to meet the 100 ppm sulfur level and the total gasoline volume.

3. 1977 Results

The volume of low sulfur, unleaded gasoline produced is approximately 30% of the total gasoline by 1977. In all cluster models except the East Coast the production of 100 ppm sulfur, unleaded gasoline was achieved by blending. Desulfurization facilities (FCC feed) were only required in the East Coast cluster model. It is reasonable to assume, then, that desulfurization facilities will not be required by 1977 in most refineries which have the flexibility to meet the 100 ppm level by blending methods.

However, for many small refiners with a limited number of blending components and treating facilities, desulfurization facilities could well be required by 1977. Although the results of the cluster models give a reasonable representation for a major portion of the U.S. refining industry, they probably do not adequately reflect the situation to be faced by the small refiner. However, many small refiners preferentially process low sulfur crude oils and may be able to avoid the need to install desulfurization facilities by 1977.

Grassroots model runs were not allowed in 1977. The total U.S. gasoline demand, taking into account gasoline imports, was assumed to be met from existing refineries.

C. MANUFACTURE OF 50 PPM GASOLINE

1. 1985 Results

As shown in Table 20, the direct desulfurization of FCC gasoline was required in the Large Midwest cluster model to meet 50 ppm sulfur in the unleaded pool, with a subsequent increase in the need for catalytic reforming. The Texas Gulf Coast cluster model also required this route to meet the 50 ppm sulfur level. The effect of the combined intakes to the FCC and coker units made it unable to meet the 50 ppm level with FCC feed desulfurization.

All other cluster models were able to meet the 50 ppm level with increased requirements for FCC feed desulfurization. In all cases the volume of gasoline produced in the cluster models was reduced when making 50 ppm gasoline compared with 100 ppm gasoline, and this loss of gasoline is made up in the grassroots models.

In the West Coast cluster model the volume of light coker gasoline in refinery fuel increased to 2.5 MB/CD to allow FCC feed desulfurization to meet 50 ppm. Light coker gasoline was also routed to refinery fuel in the Small Midcontinent model to allow FCC feed desulfurization to meet 50 ppm. The volume, however, was only 300 B/CD for the cluster model.

The grassroots models were still able to meet the 50 ppm level with desulfurization of FCC feed. The crude oil requirement was much higher for 50 ppm gasoline than for 100 ppm gasoline.

2. 1980 Results

As in the previous discussion of 100 ppm gasoline, the need to install desulfurization facilities by 1980 is reflected principally in the grassroots model. In a similar manner the cluster models for the Louisiana Gulf, Texas Gulf and West Coast did not show any requirement for desulfurization facilities; the 50 ppm gasoline being met by blending alone. However, the loss of gasoline volume as a result of the blending schemes required to meet 50 ppm gasoline is made up by the grassroots models, which do require desulfurization facilities. All regions will therefore require some form of desulfurization facilities by 1980.

Table 20. RELATIONSHIP OF CRUDE SULFUR LEVEL, FCC INTAKE AND METHOD CHOSEN TO MANUFACTURE LOW SULFUR (50 PPM) UNLEADED GASOLINE-1985

	Cluster					
	East Coast	Large Midwest	Small Midcontinent	Louisiana Gulf	Texas Gulf	West Coast
Crude sulfur level, wt %	1.08	1.4	0.53	0.33	0.76	1.14
FCC intake, % of crude run	30	35	34	37	27	25
Coker intake, % of crude run	–	10	6	8	5	20
Desulfurization option chosen	FCC feed	FCC gasoline	FCC feed	FCC feed	FCC gasoline	FCC feed

3. 1977 Results

Once again the cluster model results (with the exception of the East Coast) did not show any need for desulfurization facilities by 1977. While this is probably true of large refineries with good gasoline blending flexibility, small refineries processing high sulfur crude oils may require desulfurization facilities by 1977 to be able to manufacture 50 ppm gasoline.

D. SUMMARY OF THE ECONOMIC PENALTIES

The economic impact of manufacturing low sulfur unleaded gasoline on a U.S. aggregate basis has been calculated by scaling up the results from the cluster and grassroots model runs, using the methodology developed and discussed in Appendix G.

The capital requirements based on first quarter 1975 cost data are shown in Table 21. To manufacture unleaded gasoline with a sulfur level of 100 ppm, a total of 2.6 billion dollars (first quarter 1975 basis) will be required by 1985 and to manufacture 50 ppm gasoline a total of 4.0 billion dollars (first quarter 1975 basis) will be required by 1985. The method of calculation of capital requirements is shown in Appendix E. The capital requirements have also been inflated to estimate the final cost, and they will increase to approximately 7.0 and 10.4 billion dollars respectively.

The economic penalties in terms of cents per gallon of low sulfur gasoline produced are given in Table 22. These show that, by 1985, there will be an additional cost of 0.78 cents per gallon of unleaded gasoline to manufacture to a sulfur level of 100 ppm, and 1.63 cents per gallon to manufacture to a sulfur level of 50 ppm, relative to unleaded gasoline without sulfur control (Scenario C). These costs are based on first quarter 1975 cost levels and would be about two and a half times greater in inflated cost terms. The cents per gallon penalties are made up of five components: capital charge, operating costs, crude penalties, LPG credits and sulfur credits, details of which can be found in Appendix J. The breakdown of the 1985 penalties are shown in Table 23. The capital charge has been set at 25% of investment, crude oil has been valued at $12.50/bbl, LPG at $8.75/bbl and sulfur at $10/short ton.

Table 21. CAPITAL REQUIREMENTS TO MANUFACTURE LOW SULFUR UNLEADED GASOLINE

Millions of Dollars

	Model results for PAD I-IV							Model results for PAD-V			
	East Coast	Large Midwest	Small Midcont.	Louisiana Gulf	Texas Gulf	Grass Roots PAD I-IV	Total PAD I-IV	West Coast	Grass Roots PAD V	Total PAD V	Total U.S.A.
Non-inflated (1st Q 1975 basis)											
100 PPM gasoline											
1977	98	58	35	8	–	–	199	–	–	–	199
1980	31	34	(12)	37	26	150	266	27	180	207	473
1985	200	435	238	109	558	171	1,711	151	90	241	1,952
Total	329	527	261	154	584	321	2,176	178	270	448	2,624
50 PPM gasoline											
1977	108	54	58	9	–	–	229	–	–	–	229
1980	50	79	(58)	95	63	621	850	37	185	222	1,072
1985	271	492	309	125	490	709	2,396	179	92	271	2,667
Total	429	625	309	229	553	1,330	3,475	216	277	493	3,968
Inflated											
100 PPM gasoline											
1977	138	81	49	11	–	–	279	–	–	–	279
1980	61	66	(23)	72	51	293	520	53	352	405	925
1985	596	1,296	709	325	1,662	509	5,097	450	268	718	5,815
Total	795	1,443	735	408	1,713	802	5,896	503	620	1,123	7,019
50 PPM gasoline											
1977	152	76	81	13	–	–	322	–	–	–	322
1980	98	154	(113)	186	123	1,213	1,661	72	361	433	2,094
1985	807	1,466	921	372	1,460	2,112	7,138	533	274	807	7,945
Total	1,057	1,696	889	571	1,583	3,325	9,121	605	635	1,240	10,361

Table 22. ECONOMIC PENALTIES FOR MANUFACTURE OF LOW SULFUR UNLEADED GASOLINE[a]

CENTS PER GALLON LOW SULFUR GASOLINE

	PAD I-IV	PAD V	Total U.S.A.
100 PPM gasoline			
1977	0.25	–	0.21
1980	0.39	0.69	0.44
1985	0.78	0.84	0.78
50 PPM gasoline			
1977	0.36	–	0.30
1980	1.17	0.77	1.11
1985	1.75	0.95	1.63

[a] relative to unleaded gasoline

Table 23. BREAKDOWN OF 1985 ECONOMIC PENALTY TO MANUFACTURE LOW SULFUR UNLEADED GASOLINE[a]

(1st quarter 1975 cost basis)

		100 PPM gasoline			50 PPM gasoline	
		cents/gallon	%		cents/gallon	%
Capital charge		0.55	71		0.84	52
Operating costs		0.08	10		0.15	9
Crude penalties	0.30			1.30		
LPG credits	(0.14)	0.15	19	(0.65)	0.64	39
Sulfur credits	(0.01)	0.78	100	(0.01)	1.63	100

[a] relative to unleaded gasoline

The investment related (capital charge) penalties account for over 70% of the cost of manufacturing 100 ppm gasoline but these drop to 52% of the cost of manufacturing 50 ppm gasoline. This is because the net crude oil and products penalties increase from 0.15 cents/gallon to 0.64 cents/gallon. This reflects the significant drop in gasoline production capability that existing refineries would face in trying to manufacture 50 ppm gasoline as opposed to 100 ppm gasoline.

The capital requirements and economic penalties just described are estimates based on manufacturing unleaded gasolines with average sulfur levels of 100 ppm and 50 ppm. Should the proposed regulations require maximum specifications of 100 ppm and 50 ppm, then the target blending levels would have to be set at about 80 ppm and 40 ppm.

Based on the results of this study the capital and economic penalties in 1985 have been estimated for the manufacture of low-sulfur gasolines with maximum specifications of 100 ppm and 50 ppm and are given in Table 24. This indicates capital requirements increasing to 3.2 and 4.4 billion dollars and the economic penalties to 1.12 and 1.99 cents per gallon of unleaded gasoline, relative to unleaded gasoline without sulfur control (Scenario C).

E. SUMMARY OF CRUDE OIL AND ENERGY PENALTIES

The model results have been scaled up to give an estimate of the crude oil and energy penalties on an aggregate U.S. basis in a similar manner to that used for the economic penalties (Appendix G).

Net energy penalties are comprised of additional crude oil processed and additional purchased power required, with an energy credit taken for additional LPG produced. Table 25 gives the net energy penalties that will be incurred by 1985 to manufacture low-sulfur gasoline, relative to unleaded gasoline without sulfur control (Scenario C).

The results show that the manufacture of 100 ppm and 50 ppm gasoline will result in net energy penalties by 1985 of 42 and 160 thousand barrels per calendar day of fuel oil equivalent, respectively.

The USA will have to process 78.7 MB/CD and 343.2 MB/CD of additional crude oil to manufacture 100 ppm and 50 ppm gasoline, respectively, although

Table 24. CAPITAL REQUIREMENTS AND ECONOMIC PENALTIES FOR THE MANUFACTURE OF LOW SULFUR GASOLINE IN 1985 ASSUMING A 20% BLENDING TOLERANCE (TOTAL U.S.A.)

	100 PPM gasoline max. Blended to 80 PPM	50 PPM gasoline max. Blended to 40 PPM
Capital requirement billions of dollars (1Q 1975 basis)	3.2	4.4
Economic penalty cents per gallon low sulfur gasoline relative to unleaded gasoline (1Q 1975 basis)	1.12	1.99

Table 25. ENERGY PENALTIES IN 1985 FOR THE MANUFACTURE OF LOW SULFUR UNLEADED GASOLINE[a]

	100 PPM gasoline			50 PPM gasoline		
	PAD I-IV	PAD V	Total U.S.A.	PAD I-IV	PAD V	Total U.S.A.
Basis						
Additional crude oil required MB/CD	48.0	30.7	78.7	313.3	29.9	343.2
Additional LPG produced MB/CD	13.7	39.5	53.2	207.7	36.6	244.3
Additional purchased power required MKWH/CD	3066	687	3753	6102	758	6860
Energy penalties						
10^9 Btu/CD						
Crude oil	268	172	440	1754	167	1921
LPG	(54)	(158)	(212)	(833)	(147)	(980)
Purchased power	31	6	37	61	7	68
Total 10^9 Btu/CD	245	20	265	982	27	1009
Thousands barrels of fuel oil equivalent per calendar day	39	3	42	156	4	160

[a] relative to unleaded gasoline

it will manufacture more LPG to offset this.

Details of the 1977 and 1980 penalties are to be found in Appendix J, along with more background data on the 1985 figures.

The energy penalties described above have been based on manufacturing gasolines with average sulfur levels of 100 ppm and 50 ppm. As in the case of the economic penalties, an estimate has been made of the energy penalties that would be incurred if the gasolines were manufactured to meet maximum specifications of 100 ppm and 50 ppm. This is to reflect the fact that refineries will require blending tolerances in order to be able to ensure 100 ppm and 50 ppm gasoline production. The results based on the inclusion of blending tolerances are given in Table 26, relative to unleaded gasoline.

Table 26. ENERGY PENALTIES IN 1985 FOR THE MANUFACTURE OF LOW SULFUR UNLEADED GASOLINE WITH SULFUR BLENDING TOLERANCES OF 20%[a]

	100 PPM gasoline max. (blended to 80 PPM)			50 PPM gasoline max. (blended to 40 PPM)		
	PAD I-IV	PAD V	Total U.S.A.	PAD I-IV	PAD V	Total U.S.A.
Basis						
Additional crude oil required	154.1	30.4	184.5	366.4	29.7	396.1
Additional LPG produced	91.3	38.3	129.6	246.5	36.0	282.5
Additional purchased power required	4192	669	4861	6465	725	7190
Energy penalties						
10^9 Btu/CD						
Crude oil	863	170	1033	2052	166	2218
LPG	(366)	(154)	(520)	(989)	(144)	1133
Purchased power	42	7	49	65	7	72
Total 10^9 Btu/CD	539	23	562	1128	29	1157
Thousands barrels of fuel oil equivalent per calendar day	85	4	89	179	5	184

[a] relative to unleaded gasoline

IV. SENSITIVITY STUDY RESULTS

A. SULFUR DISTRIBUTION IN FCC UNITS

As mentioned in Section III, the assumed distribution of sulfur among the products from FCC units has been based on recent work done by Gulf Research.[15] Although the data published by the Gulf Research study is the best available, it was based on a limited number of feedstocks. Therefore, a sensitivity study was carried out to determine the effect of different FCC gasoline sulfur levels.

In the model runs, the percentage of the FCC feed sulfur that was assumed to be present in the gasoline product varied between 3.5% and 4.4% depending on feed source, with the exception of feeds from California and Alaskan North Slope crude oils. FCC gasoline from California gas oil was assumed to contain about 9.5% of the feed sulfur, and the FCC gasoline from North Slope gas oil contained about 7.0% of the feed sulfur. These percentages applied at conversion levels of 80%. The sensitivity study examined the impact of assuming all FCC gasolines contained 7.0% of the feed sulfur at the 80% conversion level. The results of the sensitivity study (completed for 1985 only) are shown in Table 27.

The sensitivity study indicated that the capital investment required would increase by 27% to manufacture 100 ppm gasoline, requiring a total of 3.3 billion dollars (IQ 1975), and by 39% to manufacture 50 ppm gasoline, requiring a total of 5.5 billion dollars (IQ 1975 basis). Economic penalties in terms of cents per gallon of low sulfur gasoline produced increased by similar amounts.

Table 27. EFFECT OF INCREASED F.C.C. GASOLINE SULFUR LEVELS ON THE 1985 ECONOMIC PENALTY FOR MANUFACTURING LOW SULFUR UNLEADED GASOLINE

	100 PPM gasoline		50 PPM gasoline	
	Base Case	Sensitivity Case	Base Case	Sensitivity Case
FCC sulfur distribution	4.7% av	7.0%	4.7% av	7.0%
Capital requirement billions dollars (1Q 1975 basis)	2.6	3.3	4.0	5.5
Economic penalty cents per gallon low sulfur gasoline relative to unleaded gasoline (1Q 1975 basis)	0.78	1.02	1.63	2.16

B. IMPORTED CRUDE OIL FOR GRASSROOTS CAPACITY

Model runs for the grassroots refineries East of the Rockies were executed for a sweet crude oil refinery (processing a 50/50 Algerian/Nigerian mix) and for a sour crude oil refinery (processing Saudi Arabian Light). The final results were scaled up on the basis that 1/3 of the grassroots capacity required East of the Rockies would be sweet crude oil capacity and 2/3 would be sour crude oil capacity. This sensitivity study examines the effects on the 1985 economic penalties if all the grassroots capacity were based on 100% sweet crude oil and also on 100% sour crude oil.

The results of the sensitivity study are given in Table 28. Only minor changes in the total U.S. economic penalties are indicated by this crude slate sensitivity study, even though a pronounced impact on the ability to produce low sulfur fuel oil would be expected.

This sensitivity study did not include the possibility that Arabian Heavy or Medium crudes could be the primary import oils as a result of Saudi Arabian marketing policy. However, based upon these results, this possibility would probably not have a major impact on the economic penalties to produce low-sulfur gasoline.

C. EFFECT OF TARGET RESIDUAL FUEL OIL SULFUR LEVEL

The sulfur level of the residual fuel oils produced in the cluster models was allowed to vary, but not to exceed a reasonable maximum specified for each cluster model. The grassroots models were then used to balance the volume of residual fuel oil required from U.S. refineries and also to balance the sulfur level of the fuel oil. Hence, the sulfur level of residual fuel oil produced in the grassroots models will depend on the target sulfur level set for the residual fuel oil produced from all U.S. refineries. A small change in the target sulfur level on residual fuel oil for the whole U.S.A. will have a significant effect on the sulfur level required of residual fuel oil produced in the grassroots models because of the leverage effect (see Section II.C.3.b) of total U.S. residual fuel oil production compared with grassroots residual fuel oil production.

Table 28. EFFECT OF CHANGING IMPORTED CRUDE OIL TYPE PROCESSED IN GRASS ROOTS CAPACITY ON THE 1985 ECONOMIC PENALTY FOR MANUFACTURING LOW SULFUR UNLEADED GASOLINE

	100 PPM gasoline			50 PPM gasoline		
	Base case	Imported crude for Grass Roots		Base case	Imported crude for Grass Roots	
		100% sour	100% sweet		100% sour	100% sweet
Crude oil sulfur, wt %	1.18	1.68	0.17	1.18	1.68	0.17
Capital requirement billion dollars (1Q 1975 basis)	2.62	2.67	2.52	3.97	3.97	3.95
Economic penalty cents per gallon low sulfur gasoline relative to unleaded gasoline (1Q 1975 basis)	0.78	0.79	0.77	1.63	1.64	1.62

The base case study assumed residual fuel oil sulfur target levels of 1.4 wt. % East of the Rockies and 0.90 wt. % West of the Rockies. This resulted in East of the Rockies grassroots residual fuel oil sulfur levels of 2.45 wt. % and 2.40 wt. % when manufacturing 100 ppm and 50 ppm gasoline, respectively. West of the Rockies grassroots production required residual fuel oil sulfur levels of 1.38 wt. % for both 100 ppm and 50 ppm gasoline.

This sensitivity study examines the effect of meeting target residual fuel oil sulfur levels for the whole of the U.S. of 1.2 wt. % East of the Rockies and 0.75 wt. % West of the Rockies. This required the East of the Rockies grassroots models to produce residual fuel oils with sulfur levels of 1.30 wt. % and 1.25 wt. % when manufacturing 100 ppm and 50 ppm gasoline, respectively. West of the Rockies required residual fuel oil sulfur levels of 0.75 wt. % for both 100 ppm and 50 ppm gasoline.

The results of this sensitivity study are given in Table 29. The effect is to increase slightly the capital requirements for the manufacture of 50 ppm gasoline. The economic penalty shows no change for manufacture of 100 ppm gasoline and a small increase for manufacture of 50 ppm gasoline. It can be concluded that the target residual fuel oil sulfur level has a relatively small impact on the cost of producing low sulfur gasoline.

D. ALTERNATIVE METHOD OF DESULFURIZING FCC GASOLINE

In Section III, an alternative method of direct desulfurization of catalytic cracker gasoline was discussed, wherein the FCC gasoline was split and only the heavy fraction desulfurized. The limited data available suggests that this method would remove 70% to 80% of the sulfur in the FCC gasoline. At the same time it would avoid having to hydrotreat the lighter, olefinic fractions in the FCC gasoline, which result in substantial loss of octane. Since the data available on sulfur distribution within FCC gasolines is limited, it is very difficult to suggest an optimal scheme which would achieve the correct balance between sulfur removal and octane loss. However, refiners who must desulfurize FCC gasolines (because FCC feed desulfurization will not meet the required sulfur level)

Table 29. EFFECT OF LOWER TARGET SULFUR LEVEL OF PRODUCTION OF U.S. RESIDUAL FUEL OIL ON THE 1985 ECONOMIC PENALTY FOR MANUFACTURING LOW SULFUR UNLEADED GASOLINE

	100 PPM gasoline		50 PPM gasoline	
	Base case	Lower residual fuel oil sulfur	Base case	Lower residual fuel oil sulfur
Capital requirement billion dollars (1Q 1975 basis)	2.62	2.55	3.97	4.04
Economic penalty cents per gallon low sulfur gasoline relative to unleaded gasoline (1Q 1975 basis)	0.78	0.78	1.63	1.67

will undoubtedly choose this alternative method of desulfurizing FCC gasolines. The more conservative approach of desulfurizing the whole FCC gasoline with subsequently large octane losses has been assumed in the study because of lack of available data on the alternative method. The capital investment requirements and economic and energy penalties calculated for the manufacture of low-sulfur gasoline are therefore conservative estimates since it is likely that they can be reduced somewhat by this alternative method of FCC gasoline desulfurization.

Most cluster and grassroots models choose the FCC feed desulfurization route to manufacture low-sulfur gasoline. The purpose of this sensitivity study is to determine if this alternative method of FCC gasoline desulfurization described above was more attractive than the feed desulfurization route. This alternative FCC gasoline desulfurization route was based upon desulfurization of the heaviest 25% fraction of the FCC gasoline, which was assumed to contain 85% of the sulfur. A clear motor octane loss of only 4 numbers was assumed when desulfurizing the heavy catalytic cracker gasoline.

The result of this sensitivity study was that the preferred route was still FCC feed desulfurization. The main reason for this choice is that, as a result of desulfurizing the FCC feed, the conversion level in the FCC unit is increased. Increased conversion levels improve yields and result in higher motor octane numbers of the FCC gasoline[16] and these benefits more than offset the higher investment cost for FCC feed desulfurization versus FCC gasoline desulfurization.

Of course, this preliminary analysis is not sufficient to indicate that, under all circumstances, refiners would wish to choose the FCC feed desulfurization route. This will depend on individual circumstances.

V. DISCUSSION

The most likely route for the majority of refiners to manufacture 100 ppm gasoline will be by FCC feed desulfurization. However, those refiners with large volumes of coking (typically found in PAD District V) may not be able to meet the 100 ppm level with FCC feed desulfurization, if all the light coker gasoline is routed to the gasoline pool. Diverting some light coker gasoline to the refinery fuel systems will probably enable the FCC feed desulfurization route to meet the 100 ppm level. Although this results in a loss of gasoline production capability, it is probably preferred to the direct desulfurization of FCC gasoline. To manufacture 50 ppm gasoline, over half of the U.S. refiners must desulfurize FCC gasoline.

The most significant conclusion that can be derived from the sensitivity studies is the importance of the assumptions with regard to the distribution of sulfur in the products from catalytic cracking. The estimated capital investment requirements to manufacture 100 ppm gasoline varied by a factor of 25% depending on the FCC unit sulfur distribution. More data on this subject is required to provide a better assessment of the penalties for the manufacture of low-sulfur gasoline.

Throughout this analysis, the impact on small refineries has not been considered in detail. The capital and economic penalties have been adjusted to minimize this effect by giving a greater weighting to the results obtained from the Small Midcontinent cluster. Refineries with a capacity of less than 50,000 barrels per day represent a small enough percentage of the total U.S. refining capacity and any understatement of the penalties they will incur will not seriously effect the overall conclusions. However, this group of refiners represents about half of the total number of refineries and they may have much more difficulty meeting the regulation than the larger refineries.

A comparison of the results of this study with the survey conducted by the NPRA[1,2] in 1974 indicates penalties of the same order of magnitude for the manufacture of low-sulfur gasoline. The NPRA survey covered 148 refineries, accounting for about 95% of the U.S. finished gasoline manufacturing capability. It indicated a capital investment requirement of some 3.7 billion dollars (average 1974 basis) to manufacture 100 ppm low-sulfur gasoline. The NPRA capital investment estimate was presumably based on the need to meet a maximum specification of 100 ppm. The range of capital investment requirements (depending on FCC gasoline sulfur levels) to meet a maximum specification of 100 ppm, based on the results of this study, would be 3.2 to 4.1 billion dollars (IQ 1975 basis).

The NPRA survey also indicated an increased fuel oil equivalent requirement of between 100,000 and 200,000 barrels per day. This compares with the estimate for this study of total energy penalties of 89,000 barrels per day of fuel oil equivalent to manufacture gasoline with a maximum specification of 100 ppm.

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